REPORT 17

SWEEP

SOIL AND WATER

ENVIRONMENTAL

ENHANCEMENT PROGRAM

PAMPA

PROGRAMME D'AMÉLIORATION

DU MILIEU PÉDOLOGIQUE

ET AQUATIQUE

Canada

Ontario

SWEEP

is a $30 million federal-provincial agreement, announced May 8, 1986, designed to improve soil and water quality in southwestern Ontario over the next five years.

PURPOSES

There are two interrelated purposes to the program; first, to reduce phosphorus loadings in the Lake Erie basin from cropland run-off; and second, to improve the productivity of southwestern Ontario agriculture by reducing or arresting soil erosion that contributes to water pollution.

BACKGROUND

The Canada-U.S. Great Lakes Water Quality Agreement called for phosphorus reductions in the Lake Erie basin of 2000 tonnes per year. SWEEP is part of the Canadian agreement, calling for reductions of 300 tonnes per year — 200 from croplands and 100 from industrial and municipal sources.

PAMPA

est une entente fédérale-provinciale de 30 millions de dollars, annoncée le 8 mai 1986, et destinée à améliorer la qualité du sol et de l'eau dans le Sud-ouest de l'Ontario.

SES BUTS

Les deux buts de PAMPA sont: en premier lieu de réduire de 200 tonnes par an d'ici 1990 le déversement dans le lac Erie de phosphore provenant des terres agricoles, et de maintenir ou d'accroître la productivité agricole du Sud-ouest de l'Ontario, en réduisant ou en empêchant l'érosion et la dégradation du sol.

SES GRANDES LIGNES

L'entente entre le Canada et les États-Unis sur la qualité de l'eau des Grands Lacs prévoyait de réduire de 2 000 tonnes par an la pollution due au phosphore dans le bassin du lac Erie. PAMPA fait partie de cette entente qui réduira cette pollution de 300 tonnes par an — 200 tonnes provenant des terres agricoles et 100 tonnes provenant de sources industrielles et municipales.

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TECHNOLOGY EVALUATION AND DEVELOPMENT SUB-PROGRAM

EFFECT OF AMMONIA ON SOIL PROPERTIES AND RELEVANCE TO SOIL AND WATER QUALITY

FINAL REPORT

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SUMMARY

Injection of anhydrous ammonia (AA) into soil causes high pH and high ammonia concentrations in an ammonia retention zone around the point of injection. These conditions might decrease soil productivity and increase erosion because they can cause hydrolysis of organic C, loss of soil structural stability, and inhibition of microbial activity. Two laboratory experiments (Experiment 1 and Experiment 2) were conducted to determine effects of AA on these soil properties and nutrient availability. In Experiment 1, three soils that ranged from 12 to 42% clay and 2.6 to 4.6% organic matter were packed moist into 15-cm long and 5.0-cm diameter columns. Soil columns were injected with reagent grade ammonium hydroxide solution (1931 mg N)at a depth of 0.5-cm below the soil surface at the top end of each column. Columns were incubated at 25°C and some were sampled at each of 1, 7, 28, and 112 days after injection. Sampling involved removing four 1-cm segments from the top of a column (depths 1 to 4) and a 1-cm segment from the bottom of the column (depth 15) for analysis. Experiment 2 was similar to Experiment 1 except that it involved only one soil, 129 mg N injected, and samplings at 1, 7, and 28 days.

Concentrations of exchangeable NH_4-N in Experiment 1 were uniform throughout the columns by day 7 and changed little to day 112. On day 7 they ranged from 1007 to 1660 mg kg^{-1}, which is similar to maximum expected concentrations in the NH_3 retention zone at usual field rates of application of AA. Maximum pH values were 8.8 to 9.2 and pH remained above 8.0 by day 112. Concentrations of water-soluble organic C increased to day 28, and then decreased to day 112 apparently because of microbial assimilation and dissimilation. Production of carbon dioxide from the soils was not detected until day 28 or later. Wet aggregate stability was initially decreased by ammonium hydroxide and then largely regained when microbial activity resumed. Ammonium hydroxide seemed to cause an increase in available P of 21% in one soil, and a decrease in available K of 3 to 14%.

On day 1 in Experiment 2, NH_4-N ranged from 760 mg kg^{-1} in depth 1 to 5.9 mg kg^{-1} in depth 15., while pH ranged from 8.6 to 6.9. Nitrification caused a continual decrease in NH_4-N to day 28, when pH was about 5.2 for all depths. Concentrations of water-soluble organic C did not significantly vary with depth and decreased from 627 mg kg^{-1} on day 1 to 380 mg kg^{-1} on day 28. Between days 7 and 28, wet aggregate stability increased while water-dispersible clay decreased for all depths.

It was concluded that AA could cause an initial loss of wet aggregate stability in the NH_3 retention zone, but this loss is likely to be regained when microbial activity resumes. Possibility of leaching of water-soluble organic C from the NH_3 retention zone by rainfall or irrigation, and long-term changes in microbial populations, might prevent regaining of structural stability under field conditions.

1.0 INTRODUCTION

This investigation into the implications of the use of anhydrous ammonia (AA) as a source of fertilizer N was commissioned by the Technology Evaluation and Development (TED) Sub-program of the Soil and Water Environmental Enhancement Program (SWEEP) of Southwestern Ontario.

The primary aims of SWEEP are the reduction of phosphorus loading to Lake Erie from cropland run-off, and the improvement of agricultural productivity in Southwestern Ontario by controlling soil degradation, a major contributor to low soil productivity and poor water quality. The TED Sub-program is concerned with evaluating existing technologies, refining them and developing new ones for the benefit of commercial farmers. It encourages the involvement of farming communities in new programs in order to facilitate the adoption of successfully developed technologies by farmers. For this reason this investigation was originally meant to be a field study in which farmers will directly participate. However, it was deemed necessary to undertake a preliminary laboratory investigation for the following reasons:

1) the amount of $30 000 earmarked for the project was inadequate for a field study on any meaningful scale,

2) the period of one year of field experimentation would not be long enough for finding any recognizable changes in soil parameters as a result of AA application,. and

3) an initial laboratory study appeared to be a better way of obtaining early information on the effect of AA on soil structural development induced by microbial activity.

Anhydrous ammonia (AA) has been known to have deleterious effects on the surface structure of soil through various mechanisms, such as reduction of organic matter, slaking of soil and killing of beneficial soil flora and fauna. The purpose of this study is to investigate changes in soil physical, chemical and biological properties resulting from the application of AA that may have implications for sustainable productivity of the soil by increasing the potential for soil erosion and the loss of phosphorous and other nutrients from cropland. The study was focused on the effect of AA on soil structure and nutrient levels, particularly the level of phosphorous. Consideration was given to the eventual field application of the findings of the study by carefully selecting soil types that will enhance the transfer of technology.

2.0 LITERATURE REVIEW

The growing use of anhydrous ammonia (AA) as a source of fertilizer N since the early 1930's led to concern about its possibly deleterious effects on soil. (Jackson and Chang, 1947; Eno and Blue, 1954; Eno et al, 1955; Andrews 1956; Ignatieff and Page, 1958, McIntosh and Frederick, 1958; Tisdale and Nelson, 1967). Andrews (1956) reviewing the deleterious effects of anhydrous ammonia on soil stated that it reduces structural stability of surface soils, increases soil pH, kills fungi and some soil fauna and decreases organic matter content of surface soils.

Destruction of soil structure has been attributed to solubilization of organic matter following application of liquid AA (Papendick and Parr, 1966). Concern about the possible adverse effect of AA on soil structure by the destruction of organic matter was rather due to speculation since the extent to which organic matter was solubilized, transformed and lost from the soil had not been investigated at that time (Nommik and Vahtras, 1982; Norman et al, 1987b). Subsequently, the quantity of organic carbon solubilized was found to be very small, relative to total organic C content of soil (Tomasiewicz and Henry, 1985; Norman et al, 1987b). Amount of C solubilized was related to soil type and found to increase with decreasing clay content (Norman et al, 1987b). This work and other recent work (Gilmour and Gilmour, 1985; Norman et al, 1988) did not support the concern expressed by earlier workers about the deleterious effects of AA. In situations where organic carbon solubilization by AA is followed by extensive microbial assimilation and appreciable decrease in organic matter content, AA might be interpreted as detrimental to soil aggregation. However, based on the very small quantities of organic carbon solubilized in soils, it seemed unlikely that serious destruction of organic matter would occur following the application of AA (Norman et al, 1987b).

Jackson and Chang (1947) pointed out that the most critical problem in the use of AA as a fertilizer is the extent of loss by diffusion into the atmosphere. A similar observation

of N losses by NH_3 volatilization on the application of AA to soil was made by others (Tisdale and Nelson, 1967; Botha and Pretorius, 1988; du Preez and Burger, 1988). The retention of AA by soils is influenced by soil texture, moisture content, pH value and soil tilth (Jackson and Chang, 1947).

Jackson and Chang (1947) found that NH_3 was absorbed instantly in medium and heavy textured soils with little loss by gaseous diffusion and that coarser textured soils retained NH_3 to approximately the same degree as the heavy textured soils. A clay content of about 6% in sandy soils was enough to provide adequate sorption capacity for NH_3. Jackson and Chang (1947) noted that there was only a slight difference between air-dry and field-moist soils in their efficacy for NH_3 sorption. Volatilization loss of N from AA did not appear to be an important factor under field conditions since the method of placement is by injection below the surface of the soil (Jackson and Chang, 1947). Several workers noted that the optimum depth of injection at which little NH_3 was lost was 5 to 10 cm (Jackson and Chang, 1947; Andrews, 1956; Papendick and Parr, 1966; Norman and Kurtz, 1986).

It has been observed that on application of AA to soil the pH at the point of injection immediately rises to 8.5 to 9.5 (Warren, 1962; Andrews, 1956). Soil pH at the point of injection has returned to its original value or less after 4 to 7 weeks in field experiments (McIntosh and Frederick, 1958) but not by 16 weeks in laboratory experiments (Norman et al, 1987a). According to Tisdale and Nelson (1967) the ultimate effect of AA on soil is to lower the pH since the conversion of NH_3 to NO_3 by nitrification is accompanied by acid formation.

A retention zone of ammonia around the point of injection of AA and observed in both field and laboratory studies (Eno et al, 1955; Parr, 1969; Hogg and Henry, 1982). Practically all fungi, nematodes and some bacteria in this zone were killed in the first few days following injection of AA, but after several days the population of bacteria and actinomycetes markedly increased (Eno et al, 1955). This fungicidal activity of AA was

looked upon by some workers as an advantage in controlling plant nematode diseases (Eno and Blue, 1954; Zrazhevskiy and Servy, 1969; Smiley et al, 1970). An inhibition of nitrification was observed within the zone of retention of NH_3, but not on the periphery (Eno and Blue, 1954). However, Norman et al (1988) and Staley et al (1988) observed an increased activity of the microbial population as indicated by increased CO_2 production after application of AA.

Detailed characterization of the nature of problems associated with the use of AA and its effect on soil were obtained through laboratory studies on soil samples (Jackson and Chang, 1947; Papendick and Parr, 1966; Jenkinson and Powlson, 1976; Norman and Kurtz, 1986, Norman et al, 1987b; Staley et al, 1988; Norman et al, 1988). However, field experiments to test some of the recent laboratory findings have been scanty.

Anhydrous ammonia is high in nitrogen content (about 82.2% N), and it is, therefore, considered as a good source of fertilizer N (Jackson and Chang, 1947; Tisdale and Nelson, 1967). However, it requires special applicators under both field and laboratory conditions (Norman and Kurtz, 1986; Papendick and Parr, 1966). Moreover, AA has been found to be extremely hazardous to health if care is not taken in its handling during field or laboratory application to soil (Krueger, 1990).

The death of a farmer who inhaled appreciable quantities of NH_3 gas while applying AA to his field near Yorkton, Saskatchewan was reported recently (Krueger, 1990).

3.0 OBJECTIVES AND HYPOTHESES

General Objectives

1. To investigate physical, chemical and biological changes in soil caused by the use of AA.

2. To evaluate the possible impact of these changes on soil and water quality and on long term soil productivity.

Specific Objectives

1. To investigate the effect of anhydrous ammonia on soil organic carbon and on soil structure;

2. To investigate the effect of AA on soil microbial activity;

3. To investigate the effect of AA on nutrients such as available P in soils;

4. To investigate the effect of AA on soil pH; and

5. To evaluate the impact of the findings on field production situations and recommend further research aimed at achieving TED objectives.

Hypotheses

For the investigations aimed at achieving the above objectives, the following hypotheses were proposed:

1. Anhydrous ammonia solubilizes organic carbon in soils and thereby destroys soil structure.

2. The application of AA to soil reduces microbial activity and thereby causes unstable aggregation in soil.

3. The application of AA renders nutrients such as P less available in soils.

4.0 MATERIALS AND METHODS

4.1 Experimental Methods

Two laboratory experiments were conducted in which soil was packed into columns and sampled at various times after injection of an NH_3 solution. Three soils in southwestern Ontario (Brookston clay from Essex Basin, Gobles loam from Kettle Basin, and Honeywood loam from Pittock Basin) (Map 1-Appendix B) were selected to provide a range in clay and organic C content (Table 1) and to be representative of cultivated soils in the area. Soils were collected in May, 1989 from the top 15-cm of fields that had been cropped to corn (Zea mays L.) in the previous year. Each soil sample (about 50 kg) was thoroughly mixed, gently crushed, passed through a 5 mm sieve, and stored in field moist conditions in plastic bags at 4°C until a day prior to use.

Soils were packed into cylindrical PVC columns (5-cm internal diameter and 15-cm long). Each column consisted of five 1-cm long segments and one 10-cm long segment. The segments were taped together using duct tape to form a vertical column with four 1-cm segments at the top (depths 1 to 4) and one 1-cm segment at the bottom (depth 15). All 90 columns required for the experiments were packed with the field moist soils, taking care to exert uniform pressure in all cases.

To determine effects of AA on soil, an NH_3 solution (reagent grade NH_4OH, assay (as NH_3) 28.0 - 30.0% (w/w), specific gravity 0.90g cm^{-3}) rather than AA was injected into soils. This procedure avoided the difficulties associated with use of pressurized AA. It was assumed that effects of NH_4OH would be equivalent to effects of AA in moist soil because equilibrium between NH_3 in the soil atmosphere and NH_3 or NH_4^+ in the solution should quickly occur whether NH_3 is added as a gas or dissolved in water.

Table 1
Selected properties of the untreated soils+

Soil	Particle Size Distribution			Moisture (1/3 bar)	pH*	Organic Matter
	Sand	Silt	Clay			
	%	%	%	%	%	%
Brookston	23.4	34.7	41.8	30.4	7.0	4.6
Gobles	45.1	36.5	18.6	18.4	7.3	2.6
Honeywood	47.1	40.5	12.4	20.2	5.8	3.3

+ Methods according to MacKeague, 1981.
* 1:1 soil to 0.01 M CaCl,

Amount of N to add to a column was calculated from an expected concentration of N in a AA band after NH_3 diffuses out into the soil, and by assuming that the top 1 cm of soil (depth 1) in a column represented the AA band. Expected concentration of N in a AA band was calculated by assuming a field rate of N application of 150 kg N ha^{-1}, a band spacing of 0.7 m, and a band radius of 2 cm after NH_3 diffused out into the soil. This concentration of N in the band (8.36 mg cm^{-3}) was multiplied by the volume of soil in a 1 cm length of soil column (19.6 cm^{-3}) to give the amount of N to add to the top 1 cm of each column (164 mg N column $^{-1}$). It was assumed in this calculation that N added to the columns was evenly distributed throughout the top 1 cm of soil.

Two experiments (1 and 2) were conducted because an error was made in the amount of NH_4OH added to the columns in 1. In 1, 9.0 cm^{-3} of NH_4OH (1931 mg N), which was about 12 times greater than the desired rate, was injected by a syringe at a depth of 0.5-cm into the top 1-cm of each column. The top and bottom of the columns were sealed with parafilm to prevent liquid from escaping. A few perforations were made on the bottom parafilm to allow exchange of gasses. The columns were incubated at 25°C for 1, 7, 28 and 112 days. On each of these 4 days some columns were disassembled and soil from each of the five 1-cm segments (depths 1 to 4 and 15) was removed for analysis.

In 2, 0.6 cm^{-3} of NH_4OH (129 mg N) was injected as in 1 to a field application rate of 118 kg N ha^{-1}. This amount of added N was slightly less than the amount specified above (164 mg) because of an error in the original calculations. Experiment 2 used only the Honeywood loam soil and columns were sampled after incubation periods of 1, 7 and 28 days.

4.2 Analytical Methods

Structural stability of soil was determined by shaking soil samples end-over-end in test tubes and measuring dispersed clay and stable aggregates greater than 0.25 mm diameter (Pojasok and Kay, 1990). Total soil, rather than a specific size fraction was used because

of the small size of samples. Duplicate subsamples were analyzed for each replicate. Results were expressed as a percentage of total soil on a weight basis.

Water-soluble organic carbon was determined using the methods of Mebius (1960) and modification by Burford and Bremner (1975). Dissolved carbon was extracted from soil using deionized water in the ratio 10:1. The solution was passed through 0.45 micron filters. The resulting solution was analyzed on a Technicon Auto Analyzer using industrial method No. 455/76W. Inorganic carbon, which is present in the samples as carbonates, was removed by sparging with 1.0 N H_2SO_4. The carbonate free soil solution was air segmented, mixed with a stream of acid and potassium persulphate and subjected to UV radiation. The resultant CO_2 generated from the organic carbon was dialysed through a silicon membrane and reacted with a weakly buffered phenolphthalein indicator. The decrease in colour of the indicator is proportional to the original water-soluble organic carbon concentration.

Ammonium (exchangeable NH_4-N) and nitrate plus nitrite were determined simultaneously on 2 M KCl extracts (10:1 ratio of solution to moist soil) using a TRAACS 800 auto-analyzer system (Alfa-Laval. AB. Stockholm, Sweden) by the methods of Tel and Heseltine (1990). Soil moisture content was determined and results were reported on an oven-dry basis.

Total carbon content of soils was determined using a Leco 70 second carbon analyzer by the method of Tabatabai and Bremner (1970).

Production of CO_2 in the soils on a sampling day was determined for each of the five 1-cm segments by incubation of each segment in air tight containers at room temperature. Air from the containers was sampled after 24 hours and analyzed for CO_2 by gas chromatography. The CO_2 evolved was expected to be a measure of microbial activity in the soil, and to indicate inhibition of activity by high NH_3 concentration and a gradual recovery of activity as NH_3 decreased with time.

Amounts of P, K, Ca and Mg and pH were determined by methods used by the Ontario Ministry of Agriculture and Food soil testing program. Phosphorus (available P) was extracted from the soil by 0.5 M sodium bicarbonate and read colorimetrically with molybdate blue colour development. Exchangeable K, Mg and Ca were extracted with neutral, normal ammonium acetate and read by atomic absorption spectrophotometer. Determination of pH was for a soil water paste.

4.3 Statistical Methods

The experiments were completely randomized factorial designs consisting of 3 soils, 4 days, 5 depths, and 3 replicates in Experiment 1, and 1 soil, 3 days, 5 depths, and 3 replicates in Experiment 2.

A repeated measures multivariate analysis of variance was conducted for each measured variable (Cole and Grizzle, 1966). Day and soil were independent variables or between subject (column) factors, while depth was a within subject factor. Depth was considered to consist of five dependent variables (depths 1 to 4 and 15) that were analyzed simultaneously as repeated measurements taken on the same experimental unit (column). This analysis does not require an assumption of equal correlations between every pair of levels within the subject factor (between every pair of depths). This assumption is required by a univariate analysis of variance and seems unlikely to hold in this experiment. The repeated measures analysis of variance and univariate analysis of variance provide identical results between subject factors (day and soil) because each method uses the same F tests. For the within subject factor (depth) and its interactions with day and soil, the repeated measures analysis of variance uses a multivariate equivalent to the univariate F test statistic. Several multivariate test statistics are available but the Pillai-Bartlett trace was chosen because it is recommended for general use in multivariate analysis of variance (Olson, 1976).

Repeated measures analysis of variance were calculated using the general linear models procedure of SAS software (SAS, 1985) with an SAS statement called "REPEATED" to specify depth as the repeated factor having five levels (1, 2, 3, 4, 15). This procedure provided multivariate and univariate tests for within subject effects (depth, depth x day, depth x soil, depth x day x soil) and univariate tests of between subject effects (day, soil, day x soil). It also provided hypotheses tests for single degree of freedom orthogonal polynomial contrasts for linear, quadratic, cubic, and quartic components of the depth effect and their interactions with day and soil. Summaries of results of the repeated measures analysis of variance are given in Appendix A (Tables 6, 7, 8 and 9). Significant levels for effects of depth and its interactions with day and soil given in Tables 6 and 8 are by the multivariate Pillai-Bartlett trace test statistic.

Correlation coefficients were calculated by the correlation procedure of SAS (1985) separately for each soil across all days and for each day. Correlations between each variable and seven most highly correlated variables are given in Appendix A (Tables 10 to 19). Correlations on each day in Experiment 1 are given only for day 1, because a clear effect of depth on ammonium concentration was not apparent after day 1. Only correlations that were significant at $p < 0.05$ are referred to in the text.

Comparisons between treatment means were made using 5% least significant difference tests calculated using between subject and within subject error variances from univariate analysis of variance. Bar graphs include a 5% LSD (depth) for comparing two depth means on the same day, and a 5% LSD (Day) for comparing two depth means on different days.

5.0 RESULTS AND DISCUSSION

5.1 Experiment 1

5.1.1 Exchangeable Ammonium-N

Amounts of exchangeable NH_4-N in soils differed between the three soils, but there was no significant interaction between soil and day or depth. Averaged over all days and depths, NH_4-N concentrations in the Brookston, Gobles, and Honeywood soils were 1667, 1017 and 1410 mg kg^{-1}, respectively (5% LSD = 212). The differences between these NH_4-N concentrations corresponded to differences in organic matter contents, but not to differences in clay contents between soils (Table 1).

Because effects of depth and day on NH_4-N concentrations did not significantly interact with soil, NH_4-N concentrations for the various depths and days were averaged over soils (Figure 1). A significant ($p < 0.05$) interaction between depth and day occurred for NH_4-N. On day 1, concentrations for depths 1 to 4 were similar and 19 to 25 times greater than the NH_4-N concentration for depth 15. On day 7, concentrations in depths 1 to 4 had decreased by about 30%, but that for depth 15 had increased greatly and was similar to NH_4-N concentrations in depths 1 to 4. Minor differences in NH_4-N concentrations occurred between depths on days 28 and 112, but generally concentrations remained similar to those on day 7 (Figure 1).

On day 7 N from the added NH_4OH seemed to be distributed evenly throughout the columns. The N moved through the soil mainly as NH_3 gas. The 15.3 M NH_4OH solution injected into the soils would generate a partial pressure of NH_3 gas of 0.25 atmospheres, which should cause rapid movement of NH_3 through the soil atmosphere.

Exchangeable NH_4-N averaged over depths on day 7 for the Brookston, Gobles, and Honeywood soils were 1662, 1007 and 1526 mg kg^{-1}, respectively. If these concentrations

occurred throughout the 15-cm length of the columns, then NH_4-N accounted for 17 to 28% of the 1931 mg N added on day 0. Less than 20% of the added N would be expected to be accounted for as clay-fixed N, organic matter-fixed N and biologically immobilized N (Norman et al, 1987a). Presumably 50% or more of the added N was lost by volatilization during incubation and/or sampling.

Concentrations of NH_4-N in depth 1 on day 1 were 2590, 1600, and 2025 mg kg^{-1} for the Brookston, Gobles and Honeywood soils, respectively. Norman et al (1987a) added AA at a rate equivalent to 206 kg N ha^{-1} to soils having clay contents of 31, 21 and 12%, and the next day measured exchangeable NH_4-N concentrations of 2800, 1500 and 1100 mg kg^{-1}, respectively, within a 1.5-cm radius of the point of injection. Although the amount of N added in the present experiment was much greater than that added by Norman et al (1987a), volatilization losses may have caused the amount of retained N to be similar to that with a usual field rate of application of AA. On day 112, NH_4-N concentrations in the Brookston, Gobles, and Honeywood soils averaged 1630, 1030, and 1200 mg kg^{-1}, respectively. These concentrations are still similar to those typically found at the point of injection of AA at usual field rates. The entire columns in this experiment, therefore, seem to represent soil subjected to the maximum NH_4-N concentrations from AA application.

5.1.2 Nitrate-N

Concentrations of NO_3-N on day 1 for the Brookston, Gobles, and Honeywood soils were 2.3 ± 1.7, 84 ± 5, and 152 ± 9 mg kg^{-1}, respectively. If these NO_3-N concentrations occurred in the top 15-cm of soil in the field, they would correspond to NO_3-N contents of 4.6, 168, and 304 kg ha^{-1} for the Brookston, Gobles, and Honeywood soils, respectively. The very high NO_3-N contents in the Gobles and Honeywood soils suggests that the samples of these soils were collected from fields that had just received N fertilizer.

Analysis of variance indicated a significant day x depth interaction for NO_3-N and the possibility of a significant day x soil interaction ($p = 0.06$). Nitrate-N concentrations are therefore presented for the various depths and days for each soil (Figure 2). For the Brookston clay, NO_3-N did not differ significantly between depths except on day 112 when the value for depth 3 was twice that for all other depths. This high value for depth 3 is probably incorrect because it resulted from one unusually high replicate value for NO_3-N out of three replicates, which were 18.4, 15.1, and 104 mg kg^{-1}. Generally, NO_3-N increased between days 1 and 7 to about 20 mg kg^{-1} and then remained constant to day 112. Analysis of variance for the Brookston clay indicated no significant day x depth interaction for NO_3-N.

Analysis of variance for NO_3-N in the Gobles loam indicated that day was the only significant effect. Average NO_3-N concentrations on days 1, 7, 28, and 112 were 84, 148, 127, and 161 mg kg^{-1}, respectively (5% LSD = 46 mg kg^{-1}). A very high value for depth 15 on day 7 (Figure 2) resulted from one high replicate value of 522 compound to the other two replicate values of 157 and 162 mg kg^{-1}. The value for depth 1 on day 112 had an unusually high coefficient of variation (48%) and is therefore questionable. It appeared that the difference in NO_3-N between day 1 and 112 mainly resulted from increased NO_3-N concentrations in depths 1 to 3 between days 1 and 7 and between days 28 and 112. The high amount of variability in the data, however makes this conclusion uncertain.

Analysis of variance for NO_3-N in the Honeywood loam indicated a significant effect of day. Average NO_3-N concentrations for days 1, 7, 28, and 112 were 153, 188, 199 and 256 mg kg^{-1}, respectively (5% LSD = 55). Significant increases in NO_3-N occurred between days 28 and 112 for depths 1 and 15. Nitrate concentrations on day 112 decreased between depths 1 and 4 and then increased to depth 15. Although the values for depths 1 and 15 were associated with a large amount of variability (C.V. depth 1 = 54%, depth 15 = 22%), the pattern of greater NO_3-N towards the ends of the columns was similar to that observed with the Gobles loam on day 112.

One possible reason for greater NO_3-N concentrations towards either end of the columns by day 112 is that concentrations of NH_3 were less at the ends of the columns and therefore less toxic to nitrifying bacteria. According to Schmidt (1982) nitrification, especially the NO_2^- oxidation step, is susceptible to inhibition by NH_3. Loss of NH_3 through the parafilm at the ends of the soil columns was indicated by an odour of NH_3 that was noticed during incubation of the columns.

Increases in NO_3-N concentrations were four to five times greater in the Gobles and Honeywood soils compared to the Brookston soil between days 1 and 112. One possible explanation for lesser nitrification in the Brookston clay is a very low population of nitrifying bacteria and a very slow growth rate of nitrifiers in this soil. A low initial population is suggested by the lack of NO_3-N in this soil on day 1. Schmidt (1982) showed that nitrifiers often have slow growth rates even under apparently favourable conditions, and cited generation times of up to 129 hours for NO_2^- oxidizers in soil.

Amounts of exchangeable NH_4-N and NO_3-N in the top 4-cm of the soil columns are given in Table 2. A significant decrease in NH_4-N occurred between days 1 and 7 for all soils, probably because of diffusion of NH_3-N into the 5 to 15 cm depths. The NO_3-N contents of the top 4-cm increased significantly between days 1 and 112 for each soil (Table 2). The changes in NO_3-N levels, however, were much too small for nitrification to have had a detectable effect on NH_4-N levels in any of the soils. Changes in total (NH_4+NO_3) N content in the top 4-cm therefore reflect changes in NH_4-N.

Table 2
Amounts of KCl - extractable N in top 4 cm of soil columns in Experiment 1 after Injecting 1931 mg N as NH_4OH at 0.5 cm depth on day 0.

Day	NH_4-N	NO_3-N	Total
	mg		
	Brookston Clay		
1	211	0.25	211
7	144	1.73	146
28	125	1.58	126
112	142	2.21	144
5% LSD	41	1.02	40
	Gobles Loam		
1	140	6.05	146
7	89	9.93	99
28	65	10.7	76
112	92	13.7	106
5% LSD	41	2.4	40
	Honeywood Loam		
1	184	12.9	197
7	132	15.1	147
28	107	16.4	123
112	104	20.2	124
5% LSD	41	4.9	40

Note: Amounts of N were calculated from concentrations by assuming soil bulk density of 1.1 g cm^{-3}.

5.1.3 Soil pH

Analysis of variance for pH indicated a significant effect of soils but this effect did not significantly interact with day or depth. Ranges of pH values observed for the Brookston, Gobles and Honeywood soils were 7.7-9.1, 7.3-9.2, and 6.6-8.8, respectively.

The lower pH values were all for depth 15 on day 1, while the upper values were for various depths on day 28. The range in pH was greatest for the Honeywood soil, apparently because it had the lowest initial pH.

A significant depth x day interaction but no significant depth x day x soil interaction occurred for pH. Averaged over the three soils, pH was greater for depths 1 to 4 compared to depth 15 on day 1, but this difference disappeared by day 7 (Figure 3). On day 28, pH values were greater than on days 1, 7, or 112. On days 1 and 7, pH was not measured immediately after sampling, and therefore might be too low because of greater volatilization of NH_3 during the time between sampling and measurement. Volatilization of NH_3 causes a decrease in pH because H^+ is formed as NH_4^+ is converted to dissolved NH_3 to maintain equilibrium.

Significant correlations between pH and NH_4-N occurred for each soil but only on day 1. Correlation coefficients on day 1 for the Brookston, Gobles, and Honeywood soils were 0.73, 0.89, and 0.84, respectively. These correlations resulted from the lower pH and NH_4-N values for depth 15 on day 1 (Figure 4). Differences in pH and NH_4-N values in depths 1 to 4 were probably too small to show a relation between pH and NH_4-N if the values for depth 15 were excluded.

A significant decrease in pH occurred between day 28 and day 112 at each depth (Figure 3). A decrease in pH would be expected to result from nitrification, which was greatest in the Honeywood loam and least in the Brookston clay (Table 2). A significant correlation between pH and NO_3-N occurred for each soil only on day 112. These correlation coefficients for the Brookston, Gobles and Honeywood soils were -0.89, -0.63, and -0.58, respectively. Comparing soils on day 112, the Honeywood loam had the greatest NO_3-N concentrations and least pH values while the Brookston clay had the least NO_3-N concentrations and greatest pH values (Figure 5). Nitrification therefore seemed to explain some of the decrease in pH between days 28 and 112 and some of the variation in pH among depths on day 112.

5.1.4 Water Soluble Organic C

Concentrations of water-soluble organic C (WSOC) presented in Figure 6 were averaged over the three soils because day and depth were the only significant effects in the analysis of variance. Values for WSOC on days 1, 7, 28, and 112 averaged 587, 771, 954, and 779 mg kg^{-1}, respectively (5% LSD = 182). Water-soluble organic C was most highly correlated with pH (r = 0.67) for the Brookston clay, exchangeable K (r = -0.42) and NO_3-N (r = 0.42) for the Gobles loam, and exchangeable Mg (r = -0.50) for the Honeywood loam. Only the correlation with pH is expected to explain the changes in WSOC. Norman et al (1987b) found that WSOC increased by six to seven times to a maximum of 700 mg kg^{-1} in one day after injection of soil with AA in a laboratory experiment, at a rate of 44 kg N ha^{-1}. Increases in pH from 6.0 or 6.5 to 9.0 or 9.5 usually accompanied the increases in WSOC (Norman et. al., 1987b). The increase in WSOC from day 1 to day 28 could therefore have resulted from an increase in pH. Alternatively, it may indicate a slow solubilization of a fraction of soil organic matter. The decrease in WSOC between days 28 and 112 may also be related to the decrease in pH. Norman et.al. (1988) found, however, that decreasing pH by addition of H_3PO_4 after application of AA, had no effect on WSOC concentrations. This test, however, involved only one soil and no comparison with results of other workers was given. Norman et. al. (1988), observed that increases in WSOC resulting from AA application gradually diminished with time back to original values before AA application. They demonstrated that the decreases could be accounted for by microbial assimilation and dissimilation. The decrease in WSOC between days 28 and 112 may therefore have been caused by microbial activity or possibly the decrease in pH.

Water soluble organic C was greater in depths 1 to 4 compared to depth 15 on day 1 (Figure 6). On days 7, 28 and 112, WSOC for depth 1 was greater than for depth 15, while that for depths 2, 3 and 4 were usually intermediate.

Concentrations of WSOC were most highly correlated with pH (r = 0.61) for the Brookston clay on day 1, NH_4-N (r = 0.52) for the Gobles loam on day 1, and NH_4-N (r = 0.72) for the Honeywood loam on day 7. A plot of WSOC versus pH for the Brookston clay indicated little or no obvious relationship on a given day, although a significant correlation occurred over all days (Figure 7). Ranges in pH values on a given day were 0.5 or less, which was too small relative to random variability in WSOC for relationships between pH and WSOC to be apparent.

5.1.5 Production of Carbon Dioxide

No measurable production of CO_2 occurred from any of the soils on days 1 and 7. On day 28, CO_2 production was detected only from the Honeywood loam. By day 112, all soils were producing CO_2 (Figure 8).

Biological and chemical reasons are both possible explanations for the lack of CO_2 production on days 1 to 28. Growth of bacteria in the soils might have been inhibited by toxic concentrations of NH_3 which gradually decreased to less toxic levels by day 112. The high rate of N application and high pH might also have caused an accumulation of NO_2, which is highly toxic to many microorganisms.

A possible chemical mechanism for the lack of CO_2 production is as pH increased to greater than 8.0, calcium precipitated as calcite and by this process used up any CO_2 that was produced. According to Lindsay (1979), calcite is most likely to control Ca solubility in alkaline soils. The reaction is:

$$Ca^{2+} + CO_{2(g)} + H_2O \rightleftharpoons CaCO_3 \text{ (calcite)} + 2H^+ \qquad \log K = 9.74$$

As pH increases from 8.0 to 9.0, Ca concentration in solution decreases from $10^{-2.5}$ M to $10^{-4.8}$ M. Until this reaction reaches equilibrium, most of the CO_2 produced in the soil might not be released.

Another possible chemical mechanism that might prevent release of CO_2 from the soils involves formation of NH_4HCO_3. This compound and its decomposition has been suggested to explain NH_3 volatilization from surface application of NH_4 compounds to calcareous soils (Feagley and Hossner, 1978). Formation of NH_4HCO_3 might occur by the reaction:

$$NH_4^+ (aq) + HCO_3^- (aq) \rightharpoonup NH_4HCO_3 (aq) \quad \log K = 0.018$$

At pH of 8.0 to 9.0, most of the injected N in solution would be as NH_4^+ rather than NH_3, most of the carbonate would be as HCO_3^- rather than H_2CO_3 or CO_3^{2-}, and NH_4HCO_3 would be predominant compared to $(NH_4)_2CO_3$. If the concentration of NH_4^+ in the soil solution was assumed to equal the total amount of N added (1981 mg N column^{-1}) divided by the volume of water in the column (assume water content 25% (w/w), soil bulk density of 1.1g cm^{-3}), and the concentration of HCO_3^- was that in equilibrium with CO_2 (assume partial pressure CO_2 in soil is ten times ambient) at a pH of 8.5, then the concentration of NH_4HCO_3 in equilibrium with NH_4^+ and HCO_3^- is:

$$[NH_4HCO_3] = Keq \times [NH_4^+] \times [HCO_3]$$
$$= 1.04 \times 1.7\ M \times 0.014\ M$$
$$= 0.025\ M$$

Generating this concentration of NH_4HCO_3 would require using about 74 mg CO_2-C kg^{-1} soil and therefore could explain the apparent lack of CO_2 production up to day 28 for the soils.

Whether CO_2 production was depressed by toxic effects of NH_3 or NO_2^-, or by chemical reactions with Ca^{2+} and NH_4^+ could not be determined. If NH_3 addition inhibited microbial activity, this effect may have largely disappeared within a few weeks as suggested by the lack of difference in CO_2 production between day 28 and 112 for the Honeywood loam (Figure 8).

Production of CO_2 on day 112 for the Brookston clay was most highly correlated (negatively) with wet aggregate stability ($r = -0.69$), suggesting that breakdown of

aggregates caused more organic C to become exposed to microbial attack. For the Gobles loam on day 112, CO_2-C was negatively correlated with NH_4-N (r = -0.64), suggesting a toxic effect on microorganisms. For the Honeywood loam on day 112, CO_2-C was negatively correlated with exchangeable Ca (r = -0.70), suggesting that Ca in solution was combining with CO_2 to form calcite.

5.1.6 Available P

All main effects and interactions in the analysis of variance for sodium bicarbonate extractable P (available P) were statistically significant. For the Brookston clay, available P values for depths 3 and 4 were greater than for other depths on days 1 and 7, but these differences disappeared by day 28 (Figure 9). On day 112, there were no differences with depth. Available P values for all depths in the Brookston clay increased between days 1 and 7 by an average of 6.6 mg kg^{-1} and then usually remained constant to day 112. Over all days and depths, P was significantly correlated only with NO_3-N (r = 0.34), but this correlation only accounted for 12% of the variation in P values for the Brookston clay.

In the Gobles loam, available P was greater for depths 1 to 3 compared to 4 and 15 on days 7 and 28, but the differences were significant only on day 7 (Figure 9). By day 112, this pattern was no longer apparent. Average P levels for each day did not change between days 1 and 112. On day 7, available P in the Gobles loam was positively correlated with WSOC (r = 0.73). Perhaps dissolution of organic matter by the added N exposed mineral surfaces that held what then became available P.

In the Honeywood loam, the only significant difference in available P among depths occurred on day 1, when P was less for depth 1 compared to all other depths (Figure 9). This difference disappeared by day 7 and no other significant differences between depths or days were observed. Available P was not significantly correlated with any other variables on day 1.

It might be expected that the increase in pH resulting from the added NH_4OH would decrease the availability of P by causing formation of insoluble calcium phosphate compounds. The higher pH values for depths 1 to 4 compared to depth 15 on day 1 should therefore have decreased P availability in depths 1 to 4 on day 1. Such a pattern of P availability with depth on day 1 was not observed in any of the soils. This lack of an effect on available P probably occurred because measurement of available P involves extraction of soil with sodium bicarbonate buffered at a pH of 8.5. Differences in soil pH therefore would not necessarily cause differences in available P at pH 8.5. An exception to this conclusion might have occurred in the Gobles loam where dissolution of organic matter by high pH might have exposed more mineral surfaces with absorbed P.

5.1.7 Exchangeable K

Significant effects in the analysis of variance for exchangeable K were day and soil. Exchangeable K values were about 50% greater in the Brookston clay compared to the Gobles and Honeywood soils (Table 3). For all soils there was a decrease in exchangeable K between days 1 and 7 and then no further change to day 112. The decreases were 3% of exchangeable K for the Brookston clay (not significant at $p=0.05$) and 14% for the Gobles and Honeywood soils.

Two possible mechanisms by which exchangeable K would be decreased are a fixation of K^+ within clay minerals and precipitation as K-aluminum-silicates at high pH. Clay minerals of the 2:1 type, especially vermiculites, can collapse when saturated with K^+ or NH_4^+ and trap NH_4^+ K^+ within the crystal lattice.

If NH_4^+ from the added NH_4OH caused collapse of clay minerals, then any K^+ in interlayer positions would become nonexchangeable. Precipitation of K as pH increases from 7.5 to 9.0 is expected to decrease K^+ concentrations from about 10^{-3} M to $10^{-4.4}$ M in the soil solution (Lindsay, 1979). Exchangeable K^+ would also be expected to

Table 3
Exchangeable K concentrations averaged over depths in Experiment 1

Soil	Day 1	Day 7	Day 28	Day 112	Mean
	mg kg^{-1}				
Brookston	295	286	286	289	289
Gobles	215	183	188	186	193
Honeywood	218	190	184	186	195
Mean	243	220	219	220	226

5% LSD (Soil x Day) = 20; (Day means) = 12; (Soil means) = 10.

decrease to maintain in equilibrium with solution K^+. Whichever mechanism was involved, its effect on exchangeable K was complete within 7 days of addition of NH_4OH and was small despite the large dose of NH_4OH.

5.1.8 Exchangeable Ca

Significant effects of soil, day, and a significant day x soil interaction were indicated by analysis of variance on exchangeable Ca. Exchangeable Ca was about two times greater for the Honeywood compared to the Brookston soil, and intermediate for the Gobles loam (Table 4). Exchangeable Ca was significantly greater on days 1 and 7 than on days 28 and 112 for the Gobles and Honeywood soils, while no effect of day occurred for the Brookston clay. The largest difference in exchangeable Ca between days was a 6.8% decrease between days 7 and 28 for the Gobles loam.

Exchangeable Ca was most highly correlated with water dispersible clay (r = 0.88) for the Gobles loam, and with water dispersible clay (r = 0.48) and CO_2-C (r = -0.48) for

Table 4
Exchangeable Ca concentrations averaged over depths in Experiment 1

Soil	Day 1	Day 7	Day 28	Day 112	Mean
	mg kg^{-1}				
Brookston	2058	2067	2012	1980	2029
Gobles	3167	3171	2955	2953	3061
Honeywood	4015	4107	3969	3978	4017
Mean	3080	3115	2979	2970	3036

5% LSD (Soil x Day) = 95; (Day means) = 55; (Soil means) = 47.

the Honeywood loam. The positive correlations with water dispersible clay seem unusual because an increase in exchangeable Ca should promote flocculation rather than dispersion of clays.

Differences in exchangeable Ca between depth 1 and depth 15 on day 1 were not statistically significant for any soil and ranged form +4% to +0.2% greater for depth 1. The differences in pH between depths 1 and 15 on day 1 therefore had no effect on exchangeable Ca. This lack of an effect of pH on exchangeable Ca might have resulted from determining exchangeable Ca at pH of 7.0. Any calcite formed at high pH would be solubilized by the neutral ammonium acetate extraction for determining exchangeable Ca.

5.1.9 Exchangeable Mg

Analysis of variance indicated significant depth x day and depth x soil interactions for exchangeable Mg. Separate analysis of variance were carried out for each soil because

standard deviations were related to Mg concentrations and these varied significantly between soils.

For the Brookston clay, analysis of variance indicated a significant effect of only depth. On day 7, exchangeable Mg was least for depth 15 and greatest for depth 1, but no significant differences occurred on other days and the pattern was not apparent on days 1 or 28 (Figure 10).

For the Gobles loam, only day had a significant effect on exchangeable Mg. Means for days 1, 7, 28, and 112 were 113, 91, 95, and 93 $mg.kg^{-1}$, respectively (5% LSD = 9.8). Exchangeable Mg was most highly correlated with exchangeable K (r = 0.38).

For the Honeywood loam, analysis of variance indicated no significant effects of day or depth or their interactions.

Increased pH resulting from addition of NH_4OH would have been expected to decrease Mg solubility and therefore exchangeable Mg, because of formation of dolomite ($MgCa(CO_3)_2$). According to Lindsay (1979), Mg^{2+} solubility in calcareous soils is controlled by a dolomite-calcite combination and should decrease from about 10^{-3} M at pH of less than 7.7 to $10^{-5.5}$ M at a pH of 9.0. The lack of an effect of pH on exchangeable Mg may have been a consequence of determining exchangeable Mg at pH of 7.0 rather than at soil pH values.

5.1.10 Aggregate Stability and Dispersible Clay

Because wet aggregate stability (WAS) and water dispersible clay (WDCL) are both indicators of soil structural stability and are expected to be correlated with each other, they will be discussed together. These measurements were made only for days 7 and 112.

Analysis of variance indicated significant day x soil x depth interactions for WAS and WDCL. For the Brookston clay, WAS on day 7 was greater at depths 2, 3, and 4 than for depths 1 and 15 (Figure 11). These values on day 7 were significantly correlated with WDCL ($r = -0.93$), which was less for depths 2, 3, and 4 compared to depths 1 and 15 (Figure 11). Dispersion of clay would cause a breakdown of microaggregates (<0.25 mm diameter) that are bound together normally by roots and fungal hyphae to form macroaggregates (>0.25 mm diameter) (Oades, 1984). The decrease in WAS at depth 1 on day 7 therefore could have resulted from the added NH_4OH causing solubilization of humus and breaking of organic matter - clay bonds that stabilize flocculated clay particles into microaggregates. The loss of WAS should decrease with distance from the point of injection, as was observed for depths 1 to 4 on day 7 (Figure 11). A reason for the decrease in WAS between depth 4 and 15 however, is not obvious.

On day 112 for the Brookston clay, WAS was less than on day 7 and did not significantly vary between depths (Figure 11). The decrease in WAS between day 7 and 112 for depths 2, 3, and 4 coincided with an increase in WDCL for these depths. Although WDCL decreased between day 7 and 112 for depth 1, a corresponding increase in WAS did not occur. Perhaps between day 7 and 112 microorganisms decomposed fungal hyphae and roots that hold microaggregates together into macroaggregates. These roots and hyphae decompose and must be renewed each year under field conditions (Oades, 1984).

Using data for both days for the Brookston clay, WAS was most highly correlated with pH ($r = -0.70$) (Figure 12). This correlation seemed to mainly result from the difference in pH between days 7 and 112. If measured pH values for day 7 are lower than actual pH values in the soil columns, then the estimated effect of pH on WAS may be exaggerated.

Wet aggregate stability for the Gobles loam on day 7 tended to increase with depth although only the differences between depths 1 and 15 and depths 3 and 15 were

statistically significant (Figure 13). On day 7, WAS was significantly correlated with NH_4-N ($r = -0.55$). Differences in WDCL with depth on day 7 seemed to account for some of the changes in WAS (Figure 13) but the differences were not statistically significant, and WAS was not significantly correlated with WDCL.

Wet aggregate stability for the Gobles loam increased between days 7 and 112 for depth 1 and decreased slightly for depth 15, so that on day 112, WAS was similar for all depths. Also, WDCL was similar for all depths on day 112 but was significantly less than on day 7 (Figure 13). This decrease in WDCL was not associated with an increase in WAS for each depth. A re-establishment of stable microaggregates was therefore not necessarily associated with an increase in stable macroaggregates as measured by WAS.

Water dispersible clay for the Gobles loam over days 7 and 112 was most highly correlated with exchangeable Ca ($r = 0.88$). Addition of the NH_4OH would have been expected to cause a replacement of Ca with NH_4^+ on exchange surfaces, resulting in an excess of Ca^{2+} in solution. Perhaps some of this Ca then formed bonds between clay and organic matter. Formation of clay-organic matter-clay bridges by polyvalent cations is a major mechanism of stabilization of clay floccules as microaggregates (Oades, 1984).

Wet aggregate stability for the Honeywood loam on day 7 was greater for depth 15 than for depths 1 to 4, and was least for depth 1 (Figure 14). It was most highly correlated with WDCL ($r = -0.81$), which was significantly less for depth 15 compared to depths 1 to 4 on day 7 (Figure 14). Also on day 7, WDCL for the Honeywood loam was most highly correlated with NO_3-N ($r = -0.84$). Because WDCL was not significantly correlated with NH_4-N or pH, a cause-effect relationship between WDCL and nitrification is unclear.

On day 112 for the Honeywood loam, WAS was significantly greater for depth 15 compared to depths 1 to 4, which were similar (Figure 14). Also on day 112, WDCL was greater for depth 15 than depth 1 and therefore would not explain the greater WAS for

depth 15. Wet aggregate stability for depths 4 and 15 did not change between days 7 and 112, while WAS for depths 1 to 3 increased from day 7. Significant decreases in WDCL occurred for all depths between days 7 and 112 (Figure 14). Over days 7 and 112, WAS for the Honeywood loam was significantly correlated with pH (r = 0.62) and WDCL (r = -0.59), while WDCL was correlated with pH (r = -0.79), NH_4-N (r = 0.56), and Ca (r = 0.48). The correlations with pH seem unusual because they indicate an improvement rather than the expected loss of structural stability with an increase in pH from 7.0 to 8.5. The other correlations suggest that as NH_4-N concentrations decreased between day 7 and 112, WDCL decreased (Figure 15) and resulted in some regaining of WAS.

For all soils, WAS on day 7 increased with distance away from the point of injection of NH_4OH. By day 112, these differences had largely disappeared and, except for the Brookston clay, WAS had increased to the values for depth 15 on day 7.

5.2 Experiment 2

This experiment was conducted using only the Honeywood loam soil with NH_4OH injected at a rate equivalent to 118 kg N ha^{-1}, and samples taken at 1, 7, and 28 days after injection.

5.2.1 Exchangeable Ammonium - N

A highly significant day x depth interaction occurred for concentration of exchangeable NH_4-N, with the cubic component of the depth effect depending upon day. Exchangeable NH_4-N decreased with depth on each day, but on day 7 the difference between depths 1 and 2 was not statistically significant (Figure 16). From day 1 to day 7 NH_4-N decreased in depths 1 to 3 but the effect was significant only for depth 1. Exchangeable NH_4-N increased between day 1 and 7 in depth 4 and then decreased to day 28 for depths 1 to 4. The concentration of NH_4-N at depth 15 ranged from 2.6 to

5.9 mg kg^{-1}, suggesting that the soil for this depth could be regarded as a control. This conclusion agrees with that of Nommick and Vahtras (1982), who stated that the ultimate diameter of the NH_3 retention zone around the point of injection is not expected to exceed 10 or 12 cm at usual field application rates of N.

Exchangeable NH_4-N in depth 4 on day 1 accounted for 7% of the total exchangeable NH_4-N in depths 1 to 4 on day 1. Less than 10% of the added N would therefore be expected to have diffused beyond depth 4 by day 1. If soil bulk density was 1.1g cm^{-3}, then exchangeable NH_4-N in depths 1 to 4 on day 1 amounted to 44.2 mg or 34% of the N added. This recovery seems very low compared to a recovery of 90% or more of added N as exchangeable NH_4-N reported by Norman et al (1987a) at one day after injecting anhydrous NH_3 into soils ranging in clay content from 12 to 31%. The low recovery of added N suggests that a large amount of N was lost by volatilization through the parafilm and/or during sampling. If the unrecovered N on day 1 was lost by volatization through the parafilm, then the stated rate of N applied in terms of an equivalent field application should be adjusted downwards.

5.2.2 Nitrate - N

A significant depth x day interaction occurred for NO_3-N. On day 1 there was no significant difference in NO_3-N between depths (Figure 17). On day 7, NO_3-N was greater in depths 3 and 4 compared to depths 1 and 15. On day 28, NO_3-N was greater for depth 1 than for depths 3, 4, and 15. A significant increase in NO_3-N between days 1 and 28 also occurred in depth 15, presumably from nitrification of NH_4^+ supplied by mineralization of organic matter. This mineralization did no increase NH_4-N concentration in depth 15 (Figure 17) probably because the NH_4^+ was oxidized to NO_3^- as rapidly as it was formed.

Rates of increase in NO_3-N concentration between days 1 and 7 for depths 1, 2, 3, and 4 were 11.4, 13.7, 23.4 and 22.4 mg kg^{-1} day^{-1}, respectively (95% C.I. = ±11.7). Between

days 7 and 28 the rates of increase for these depths were 15.1, 11.2, 6.9, and 2.4 mg $kg^{-1}day^{-1}$. Rates of nitrification therefore seemed to be greatest at depths 3 and 4 prior to day 7 and at depths 1 and 2 after day 7. A similar pattern was reported by McIntosh and Frederick (1958) who found that maximum nitrification rates occurred at about 2.5-cm from the point of injection of anhydrous NH_3 but this position gradually moved towards the point of injection as pH there decreased. Paul and Clark (1989) state that optimum pH for nitrification varies between 6.6 and 8.0, and nitrification decreases greatly below a pH of 6.0. Soil pH on day 1 was greater than 8.0 in depths 1 and 2 and 8.0 or less ind depths 3 and 4. On day 7, pH was 8.0 or less at all depths. The greater rates of NO_3-N production in depths 3 and 4 compared to depths 1 and 2 therefore probably resulted from inhibition of nitrification by high pH. The added N did not clearly promote nitrification in depths 1 and 2 until after day 7 (Figure 17).

5.2.3 Soil pH

A significant depth x day interaction occurred for soil pH. On day 1, pH was 8.6 in depth 1 and progressively decreased to 6.9 in depth 15, although the difference in pH between depths 1 and 2 was not significant (Figure 18). On day 7 pH decreased with depth but the differences between depths 1 and 2 and between depths 4 and 15 were not significant. On day 28 there were no significant differences in pH between depths and average pH on day 28 was 5.2. Decreases in pH occurred between day 1 and 7 and between days 7 and 28 for each depth. The maximum pH of 8.6 for depth 1 on day 1 was less than maximum pH values of 9.1 to 9.5 reported by McIntosh and Frederick (1958) and Norman et al (1987a) for soil within 1.5 or 2.5 cm of the point of injection of AA.

On day 1 and day 7 pH was most highly correlated with NH_4-N ($r = 0.99$ for day 1, $r = 0.93$ for day 7). Over all depths and days, pH was positively correlated with NH_4-N ($r = 0.76$) and negatively correlated with NO_3-N ($r = -0.75$). The effect of NH_3 from the added NH_4OH was therefore to raise the pH. As incubation progressed, nitrification

occurred causing acid formation and a lowering of pH to below the original pH. This pattern agrees with findings of others (Norman et al 1988; Tisdale and Nelson, 1976; Warren, 1962; Andrews, 1956).

At lower concentrations of NH_4-N (less than 600 mg kg^{-1}), pH on day 7 tended to be less than pH on day 1 (Figure 19). The lesser pH is expected to have resulted from greater nitrification, suggesting that nitrification was inhibited when NH_4-N concentration was greater than 600 mg kg^{-1} or when pH was greater than 8.0.

5.2.4 Water Soluble Organic C

Analysis of variance indicated that only day had a significant effect on water-soluble organic C (WSOC). Averaged over depths, WSOC on days 1, 7, and 28 were 627, 508, and 380 mg kg^{-1}, respectively (5% LSD = 65). No significant differences in WSOC between depths occurred on any day, and trends in WSOC with depth were not consistent between days (Figure 20).

Over all days and depths, WSOC was most highly correlated with pH ($r = 0.75$) (Figure 21) and CO_2-C ($r = 0.75$). The closeness of the relationship between WSOC and pH ($r^2 = 0.57$) and the slope of the linear regression was similar to that reported by Norman et al (1987b) after they injected AA at 44 or 206 kg N ha^{-1} into soil having a clay content of 12%. The decrease in WSOC with time is therefore possibly a result of the decrease in pH. Another likely cause is microbial assimilation (conversion to microbial biomass) and dissimilation (CO_2 production) of the WSOC. Norman et. al. (1988) concluded that all organic C solubilized by AA was transformed by microorganisms within 35 days of application of AA. In their experiment with a silty clay loam soil, WSOC at one day after AA application increased from 25 to 282 mg kg^{-1}. Over the next 35 days, AA treated soil had a cumulative CO_2-C production of 630 mg kg^{-1} compared to 200 mg kg^{-1} for untreated soil. Microbial processes therefore might largely account for the decreases in WSOC.

The lack of an effect of depth on WSOC contradicts results of Normal et.al. (1986b) who found that one day after injecting 44 kg N ha^{-1} as AA in a laboratory experiment, WSOC was 475 mg kg^{-1} within a 1.5-cm radial zone of the point of injection and 243 mg kg^{-1} in a 3.0 to 4.5 cm zone. The soil had a 12% clay content and exchangeable NH_4-N was 798 mg kg^{-1} in the 1.5-cm zone and 318 mg kg^{-1} in the 3.0 to 4.5 cm zones. Using the linear regression of WSOC on pH for the Honeywood loam (Figure 21), predicted values of WSOC for depths 1 and 15 on day 1 are 635 and 517 mg kg^{-1}, respectively. The predicted difference of 118 mg kg^{-1} is only slightly larger than the 5% LSD value for depth (98). Lack of a consistent pattern of decreasing WSOC with depth, or of a significant correlation between WSOC and pH on any day, probably resulted from the large amount of random variation in the WSOC data.

5.2.5 Production of Carbon Dioxide

Analysis of variance indicated that there was a significant depth x day interaction for CO_2-C. On day 1 production of CO_2 was significantly greater in depths 3 and 4 compared to depths 1, 2, and 15, which did not differ in CO_2 production (Figure 22). On day 7 production of CO_2 was greater in depths 1, 2, and 3 than in depths 4 and 15. On day 28 there were no significant differences in CO_2 production among depths.

On day 1 the greater CO_2 production in depths 3 and 4 compared to depth 15 suggests that injection of NH_4OH initially promoted microbial activity at the periphery of the NH_3 retention zone. The NH_4OH increased soil pH, which probably caused an increase in WSOC and therefore an increase in available C for microbial respiration.

Less CO_2 production from soil in depths 1 and 2 compared to depths 3 and 4 on day 1 indicated chemical fixation of CO_2 by formation of $CaCO_3$, or inhibition of microbial activity by NH_3 toxicity. Toxicity was suggested by Parr (1969) who used soil dilution and plate count techniques to enumerate soil microorganisms nine days after starting aeration of treated soil with NH_3-free air. The soil had received AA-N at a rate of 7500

mg kg^{-1} (compared to 6000 mg kg^{-1} added to depth 1 in Experiment 2) and was then incubated for 24 hours before beginning aeration. Numbers of actinomycetes and bacteria after nine days for control and treated soil were 427 x 10^6 and 18.6 x 10^6 g^{-1} soil, respectively. Numbers of fungi for control and treated soils were 18.7 x 10^3 and 0 g^{-1} soil, respectively (Parr, 1969). A decrease in microbial population therefore seems the most likely reason for less CO_2 production in depths 1 and 2 compared to depths 3 and 4 on day 1.

Averaged over depths, CO_2-C production on days 1, 7, and 28 was 17.7, 7.3, and 3.1 mg kg^{-1} (5% LSD = 1.3). This decrease in CO_2-C was most highly correlated with WSOC (r = 0.75). Whether the decrease in WSOC was mainly due to decreasing pH or due to microbial respiration could not be determined.

5.2.6 Aggregate Stability and Dispersible Clay

Analysis of variance for wet aggregate stability (WAS) and water dispersible clay (WDCL) indicated that day was the only significant effect for either variable.

Averaged over all depths, WAS increased from 21.3 to 31.1% while WDCL decreased from 1.3% to 0.61% between days 7 and 28 (Table 5). Using all data points, WAS was most highly correlated with WDCL (r = -0.86) while WDCL was most highly correlated with pH (r = 0.87) (Figure 23).

The correlations suggest that the increase in WAS between days 7 and 28 resulted from the decrease in WDCL, which resulted from the decrease in pH from 7.1 on day 7 to 5.2 on day 28. The decrease in pH could have caused the decrease in WDCL by causing precipitation of WSOC and formation of bonds between this organic matter and clay particles. Although WAS is a measure of macroaggregate stability, which usually depends upon a mesh of roots and fungal hyphae, a sufficient quantity of mucilage or humus associated with metal ions and spread uniformly through the soil could stabilize

Table 5
Wet Aggregate Stability (WAS) and water dispersible Clay (WDCL) in Honeywood loam at 7 and 28 days after injecting NH_4OH in Experiment 2

Depth	Day 7		Day 28	
	WAS	WDCL	WAS	WDCL
	%			
1	21.3	1.51	35.8	0.50
2	20.3	1.69	32.2	0.49
3	21.1	1.28	28.8	0.75
4	22.6	1.23	29.1	0.64
15	21.0	1.24	29.9	0.68
5% LSD (Day)	6.3	0.39		
5% LSD (Depth)	3.9	0.38		

stabilize macroaggregates (Oades, 1984). Precipitation of WSOC as pH decreased because of nitrification, was therefore a possible cause of the increase in WDCL and increase in WAS between days 7 and 28. Production of mucilage by microorganisms because of increased WSOC may also have contributed to improved soil stability.

Effects of the added NH_4OH on WAS or WDCL were not indicated by analysis of variance, but unprotected LSD tests and trends with depth suggested effects did occur. On day 7 there were no differences in WAS among depths but WDCL was greater in depths 1 and 2 compared to depths 3, 4, and 15 (Table 5). On day 7 WDCL was positively correlated with pH ($r = 0.62$), suggesting that increase pH resulting from NH_3 caused an increase in WDCL, probably by solubilization of organic matter. A corresponding decrease in WAS would not necessarily be expected because the roots and

hyphae that stabilize macroaggregates are generally resistant to chemical treatments. Also, if dispersion of clay mainly occurred at the surface of macroaggregates and most macroaggregates were significantly larger than the 0.25 mm sieve openings, then a small increase in WDCL might not have a measurable effect on WAS.

On day 28 WAS for depth 1 was significantly greater than that for depths 3, 4, and 15 (Table 5). Values for WAS on day 28 were most highly correlated with total N (NH_4-N+NO_3-N)($r = 0.72$). A possible explanation for greater WAS in depth 1 is this depth would have been subjected to the greatest redistribution of organic matter because of solubilization by high pH and subsequent precipitation as pH decreased. Most aggregates would increase in stability compared to initial values if a more uniform distribution of organic matter resulted in more clay-organic molecule bonds (Gifford and Strickling, 1958).

No significant differences in WDCL occurred between depths on day 28 (Table 5) and WDCL was not significantly correlated with any other variables on day 28. Differences in WDCL on day 28 therefore did not seem to be a major cause of differences in WAS.

6.0 GENERAL DISCUSSION

6.1 Soil Structure and Organic C

A decrease in WAS seemed to be an initial effect of a high rate of application of NH_4OH to soils. In Experiment 1, WAS on day 7 (earliest measurement) was greater for depth 15 compared to depths 1 to 4 for the Gobles loam (Figure 13) and Honeywood loam (Figure 14), and greater for depths 2, 3, and 4 compared to depth 1 for the Brookston clay (Figure 11). In Experiment 2 however, there was no effect of depth on WAS on day 7, suggesting no initial effect of NH_4OH on WAS (Table 5). If concentrations of NH_4-N in depth 1 on day 1 occurred in an AA band in the field, then field rates of application would be 41 kg N ha^{-1} in Experiment 1 and 15 kg N ha^{-1} in Experiment 2. At usual field rates of application of AA, some initial loss of WAS in the NH_3 retention zone therefore seems likely.

Initial loss of WAS by application of NH_4OH resulted from a breakdown of macroaggregates (slaking) by detachment of microaggregates, with or without dispersion of clay. For Brookston and Honeywood soils in Experiment 1, WAS on day 7 was most highly correlated (negatively) with WDCL. An increase in dispersed clay therefore seemed to cause the loss of WAS. For the Gobles loam, WAS on day 1 was negatively correlated with NH_4-N but not significantly correlated with WDCL. Detachment of microaggregates may have caused the loss of WAS upon addition of NH4OH in this soil. Reasons for the different responses between soils were not evident.

The initial decreases in WAS had largely disappeared by day 112 in Experiment 1, probably because of stabilization of macroaggregates and microaggregates by mucilage compounds produced by microorganisms. In Experiment 1, WAS increased between days 7 and 112 in depth 1 for the Gobles loam (Figure 13) and in depths 1 to 3 for the Honeywood loam (Figure 14). These increases in WAS were associated with decreases in WSOC of about 100 to 200 mg kg^{-1}, which probably resulted from microbial

assimilation and dissimilation (Norman et al, 1988). Mucilage produced by these microorganisms would be expected to increase WAS. Decreases in WAS occurred between days 7 and 112 in all depths for the Brookston clay (Figure 12) and were associated with increases in WSOC of 200 to 400 mg kg^{-1}. The NH_4OH was still causing a net solubilization of organic C in this soil, which had the highest concentrations of NH4-N.

In Experiment 2 WAS averaged over all depths increased from 21.3% on day 7 to 31.2% on day 28, and was associated with a decrease in WSOC of 128 mg kg^{-1}. On day 28 WAS in depth 1 was significantly greater than in depths 3, 4, and 15 (Table 5). An increase in WAS in laboratory and field experiments after application of AA was also reported by Gifford and Strickling (1958). It seemed likely therefore that any initial loss of WAS caused by AA would be recovered soon after microbial activity resumed.

Under field conditions, WAS might not be regained or increased if WSOC was leached from the NH_3 retention zone. In these experiments initial WSOC concentrations were very high, perhaps because soil was collected during spring or because of prolonged storage at 4°C. Concentrations of WSOC in field soil at the time of AA application might be minimal because of microbial activity. If the additional WSOC in the NH_3 retention zone is removed by leaching, then bacteria might produce less mucilage and regaining of WAS would be delayed. Application of AA to give NH_3 concentrations that are not highly toxic to microorganisms would decrease the possibility of WSOC being leached from the AA band before it was utilized by microorganisms.

If WAS is not regained, then the deterioration of soil structure over several years of application of AA would result in increased potential for soil erosion and P losses by run-off. A decrease in WAS would cause a decrease in hydraulic conductivity, while dispersion of clay would cause a decrease in porosity (poorer aeration) and increased soil strength. Because the NH_3 retention zone is expected to include less than 20% of the plow layer of soil (Nommik and Vahtras, 1982), erosion potential of the soil might not

be affected until after several years of AA application. Results of Experiment 1 and 2 suggest however that any losses of WAS in the AA band would be quickly regained probably because of mucilage produced by bacteria.

6.2 Microbial Activity

Measurement of CO_2-C production was probably an adequate indicator of microbial activity. Production of CO2 in the soils in Experiment 1 was detected by day 28 or 112 and was negatively correlated with NH_4-N or Ca on day 112. The lack of CO2 production on day 28 and earlier might have resulted from formation of NH_4HCO3 and $CaCO_3$, but probably mainly resulted from toxic effects of NH_3. Concentrations of WSOC increased between days 1 and 28, suggesting little or no microbial activity. Between days 28 and 112, WSOC decreased and CO_2 was detected from all soils. In Experiment 2, production of CO_2 decreased between days 1 and 28 and was positively correlated with WSOC. In this experiment CO_2 production was promoted at the periphery of the NH_3 retention zone on day 1 and then within the retention zone on day 7 (Figure 22), suggesting no significant NH_3 toxicity by day 7.

Nitrification was the main mechanism for decreasing NH_4-N and pH in the retention zone, but was also inhibited by high pH and NH_4-N concentrations. Negative correlations occurred between pH and NO_3-N in Experiment 1 and Experiment 2. In Experiment 1 nitrification rates in depths 1 to 15 between days 1 and 112 were less than 10% of those for depth 15 between days 1 and 7, indicating an inhibition of nitrification. Nitrification rates were about three times greater in the Honeywood compared to the Brookston soil mainly because of the greater initial nitrifying capacity of the Honeywood soil. In Experiment 2 nitrification was promoted by NH_4OH but to a lesser extent in depths 1 and 2 where pH was greater than 8.0. Nitrifying capacity would seem to be a key factor in determining how quickly microbial activity, and consequently aggregate stability, is regained after application of AA.

Re-establishment of microbial activity after application of AA may result in a different equilibrium of microbial populations. Parr (1969) found that ammoniated soils were much more quickly recolonized by bacteria and actinomycetes than by fungi. It was not known whether this effect would be beneficial or harmful to crop growth.

6.3 pH and Nutrient Availability

Application of NH_4OH increased soil pH to 8.8 to 9.2 in Experiment 1 and to 8.6 in Experiment 2. High pH from NH_4OH seemed to cause an increase in sodium bicarbonate extractable P (available P) in the Brookston clay. Available P in this soil increased from an average of 32.4 mg kg^{-1} on day 1 to 38.9 mg kg^{-1} on day 7, and then changed little to day 112. This increase may have resulted from soil pH values being greater than 8.5, which is the pH at which available P is extracted. At higher pH values more organic C would by solubilized, exposing more adsorbed P on mineral surfaces. The relatively small effect on available P however would disappear once organic matter is redeposited on the mineral surfaces by microbial activity. Application of AA to soils therefore would not be expected to cause substantial long term changes in available P.

Effects of high pH from AA or low pH from nitrification on availability of P to plants depends on to what extent the plant regulates pH of rhizosphere soil from which P is absorbed. Greatest availability of P occurs in a pH range of 6.0 to 6.5. Plants can increase or decrease rhizosphere pH in response to N supply (NH_4 or NO_3) and availability of P. Effects of AA or nitrification on pH of bulk soil therefore may have little effect on availability of P to plants.

Concentrations of exchangeable K seemed to be decreased by addition of NH_4OH to the Gobles and Honeywood soils. Exchangeable K decreased from 215 mg kg^{-1} on day 1 to 183 mg kg^{-1} on day 7 for the Gobles loam, and from 218 to 190 mg kg^{-1} for the Honeywood loam. High concentrations of NH_4-N may have caused collapse of 2:1 clay minerals (mainly vermiculite) resulting in fixation of K between clay sheets. Under field

conditions this fixed K could become slowly available to crops over one or more growing seasons. Application of AA is therefore expected to cause some decrease in K availability in the NH_3 retention zone when applied to soils having a significant content of clay minerals able to fix K.

Exchangeable Ca and Mg both decreased during Experiment 1, suggesting a negative effect of NH_4OH on Ca and Mg availability. Between days 1 and 112 exchangeable Ca in the Brookston, Gobles, and Honeywood soils decreased by 78 (3.8%), 215 (6.7%), and 37 mg kg^{-1} (0.1%), respectively. Decreases in exchangeable Mg occurred between days 1 and 28 and were 38 (11%), 18 (16%), and 19 mg kg^{-1} (9%) for the Brookston, Gobles, and Honeywood soils, respectively. The decreases may have resulted from calcite and dolomite that formed at high pH and did not completely dissolve during extraction of soil at pH 7.0. The small effects on available Ca and Mg suggest that significant decreases in available Ca and Mg would not be expected from application of AA.

7.0 CONCLUSIONS

Large losses of N by volatilization seemed to occur in these experiments and made it difficult to estimate rates of N application in terms of field application of AA. Maximum concentrations of exchangeable NH_4-N suggested that Experiment 1 approximated an upper limit and Experiment 2 a lower limit of expected maximum NH_4-N concentrations in the NH_3 retention zone after field application of AA. For soil in the NH_3 retention zone, it is therefore concluded that:

1) Wet aggregate stability is initially decreased at high NH_4-N concentrations, but is regained or increased once microbial activity resumes.

2) Microbial activity is inhibited at high NH_4-N concentrations but is associated with decreases in water soluble organic C after activity resumes.

3) Significant long-term changes in levels of available nutrients (P, K, Ca, Mg) seem unlikely to occur in the AA band, except possibly a decrease for K when K-fixing clay minerals are present.

Effects of AA on WAS in field conditions might vary from effects in laboratory experiments because of leaching of the retention zone by rainfall or irrigation. Also, long-term effects of AA applications on soil microbial populations, especially fungi, may have important implications for soil structure and crop growth. Further research could involve field experiments to determine effects of AA on soil structure and microbial populations in the NH_3 retention zone during one or more growing seasons.

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APPENDIX A

ANALYSIS OF VARIANCE AND CORRELATIONS

Table 6
Significance Levels (Pr > F) for main effects and interactions of day (D), soil (S), and depth (De) from analysis of variance for variables in Experiment 1.

Variable	D	S	D x S	De	De x D	De x S	De x Dx S
Exch. NH_4-N	***	***	0.92	***	***	0.12	0.17
Ext. NO_3-N	***	***	0.06	*	*	0.35	0.40
Exch. + Ext. N	**	***	0.95	***	***	0.06	0.15
pH	***	***	0.55	***	**	0.17	0.06
Wet Agg. Stabil.†	0.22	*	***	**	*	*	*
Water Disp. Clay†	***	***	***	*	***	*	**
Water Sol. Org. C	**	0.16	0.27	**	0.23	0.22	0.75
CO_2-C‡	0.93	0.07	-	0.50	0.87	0.17	-
Ext. P	***	***	**	**	*	**	*
Exch. Ca	***	***	0.05	0.19	0.17	0.35	0.29
Exch. Mg	0.08	***	0.77	0.07	*	*	0.08
Exch. K	***	***	0.50	0.26	0.20	0.16	0.90
Total C	0.70	***	0.10	0.99	0.14	0.87	0.91

† Determined for days 7 and 112 only.
‡ Data included values for day 28 for Honeywood soil, and for day 112 for all soils.

Note: ***, **, and * indicate that Pr > F is ≤ 0.001, ≤ 0.01, and ≤ 0.05, respectively.

Table 7
Highest significant [(Pr > F) ≤0.05] polynomial contrast for depth and significance levels for the contrast (C) and its interactions with day (D) and soil (S) in Experiment 1.

Variable	Contrast	Significance Level			
		C	D	S	D x S
Exch. NH_4-N	Linear	***	***	0.33	0.18
Ext. NO_3-N	Linear	**	0.28	0.05	0.26
Exch. + Ext. N	Linear	***	***	0.15	0.19
pH	Quartic	*	0.22	0.87	0.28
Wet Agg. Stabil.	Quartic	*	*	0.63	0.82
Water Disp. Clay	Quadratic	***	***	***	***
Water Sol. Org. C	Quadratic	**	*	0.31	0.77
CO_2-C	ns	-	-	-	-
Ext. P	Quadratic	*	0.42	***	0.24
Exch. Ca	ns	-	-	-	-
Exch. Mg	Linear	*	**	***	**
Exch. K	ns	-	-	-	-
Total C	ns	-	-	-	-

Note: ***, **, * and ns indicate that Pr > F is ≤ 0.001, ≤ 0.01, ≤0.05 and >0.05, respectively.

Table 8
Significance levels (Pr > F) for main effects and interactions of day (D) and depth (De) from analysis of variance for variables in Experiment 2.

Variable	D	De	D x De
Exch. NH_4-N	***	***	***
Ext. NO_3-N	***	*	*
Exch. + Ext. N	0.16	***	*
pH	***	***	**
Wet Agg. Stabil.†	**	0.12	0.12
Water Disp. Clay†	***	0.92	0.38
Water Sol. Org. C	***	0.58	0.51
CO_2-C	***	**	**

† Determined for days 7 and 28 only.

Note: ***, ** and * indicate that Pr > F is ≤ 0.001, ≤ 0.01, and ≤ 0.05, respectively.

Table 9
Highest significant [(Pr > F) ≤0.05] polynomial contrast for depth and significance levels for the contrast (C) and its interactions with day (D) in Experiment 2.

Variable	Contrast	Significance Level	
		C	D
Exch. NH_4-N	Cubic	***	**
Ext. NO_3-N	Quartic	*	0.17
Exch. + Ext. N	Quartic	*	*
pH	Cubic	**	**
Wet Agg. Stabil.	Quadratic	*	**
Water Disp. Clay	ns	-	-
Water Sol. Org. C	ns	-	-
CO_2-C	Quartic	*	*

Note: ***, **, * and ns indicate that Pr > F is ≤ 0.001, ≤ 0.01, ≤ 0.05 and >0.05, respectively.

Table 10: Pearson correlation coefficients / prob > |R| under Ho: Rho=0 / number of observations, for each variable with seven most highly correlated variables, for Brookston clay in Exp. 1

P

P	WAS	NO3N	WDCL	K	CO2C	PH
1.00000	0.34359	0.34079	-0.29009	-0.20466	0.16670	0.09115
0.0	0.0630	0.0077	0.1199	0.1167	0.5526	0.4885
60	30	60	30	60	15	60

K

K	CO2C	MG	TOTC	WDCL	P	CA
1.00000	0.29850	-0.28927	0.28593	-0.26624	-0.20466	0.20261
0.0	0.2798	0.0250	0.0268	0.1550	0.1167	0.1205
60	15	60	60	30	60	60

MG

MG	CO2C	K	PH	TOTN	NH4N	TOTC
1.00000	-0.36650	-0.28927	-0.24071	0.17956	0.17952	0.14340
0.0	0.1791	0.0250	0.0639	0.1698	0.1699	0.2744
60	15	60	60	60	60	60

CA

CA	WAS	WSOC	PH	NH4N	TOTC	TOTN
1.00000	0.56582	-0.31053	-0.25571	0.22180	0.21945	0.21923
0.0	0.0011	0.0157	0.0486	0.0885	0.0921	0.0924
60	30	60	60	60	60	60

PH

PH	WAS	WSOC	CO2C	CA	TOTC	MG
1.00000	-0.69810	0.66856	0.28456	-0.25571	-0.24891	-0.24071
0.0	0.0001	0.0001	0.3040	0.0486	0.0551	0.0639
60	30	60	15	60	60	60

NH4N

NH4N	TOTN	CO2C	NO3N	CA	MG	TOTC
1.00000	0.99976	0.52166	-0.25246	0.22180	0.17952	0.07285
0.0	0.0001	0.0461	0.0516	0.0885	0.1699	0.5801
60	60	15	60	60	60	60

NO3N

NO3N	WSOC	P	NH4N	TOTN	CO2C	CA
1.00000	0.35651	0.34079	-0.25246	-0.23127	-0.21515	-0.16771
0.0	0.0052	0.0077	0.0516	0.0754	0.4413	0.2002
60	60	60	60	60	15	60

Table 10. (continued).

WSOC

WSOC	PH	WAS	NO3N	CA	TOTC	CO2C
1.00000	0.66856	-0.53626	0.35651	-0.31053	-0.27358	0.18167
0.0	0.0001	0.0023	0.0052	0.0157	0.0344	0.5170
60	60	30	60	60	60	15

CO2C

CO2C	WAS	TOTC	TOTN	NH4N	WDCL	MG
1.00000	-0.68924	0.58975	0.54024	0.52166	0.46541	-0.36650
0.0	0.0045	0.0207	0.0376	0.0461	0.0804	0.1791
15	15	15	15	15	15	15

TOTC

TOTC	CO2C	WDCL	K	WSOC	PH	CA
1.00000	0.58975	-0.31256	0.28593	-0.27358	-0.24891	0.21945
0.0	0.0207	0.0926	0.0268	0.0344	0.0551	0.0921
60	15	30	60	60	60	60

WAS

WAS	PH	CO2C	CA	WSOC	WDCL	P
1.00000	-0.69810	-0.68924	0.56582	-0.53626	-0.53419	0.34359
0.0	0.0001	0.0045	0.0011	0.0023	0.0024	0.0630
30	30	15	30	30	30	30

WDCL

WDCL	WAS	CO2C	TOTC	P	K	CA
1.00000	-0.53419	0.46541	-0.31256	-0.29009	-0.26624	-0.18399
0.0	0.0024	0.0804	0.0926	0.1199	0.1550	0.3304
30	30	15	30	30	30	30

TOTN

TOTN	NH4N	CO2C	NO3N	CA	MG	TOTC
1.00000	0.99976	0.54024	-0.23127	0.21923	0.17956	0.07267
0.0	0.0001	0.0376	0.0754	0.0924	0.1698	0.5811
60	60	15	60	60	60	60

Table 11: Pearson correlation coefficients / prob > |R| under Ho: Rho=0 / number of observations, for each variable with seven most highly correlated variables, for Gobles loam in Exp. 1

P	P	CO2C	WSOC	TOTC	WDCL	WAS	MG
	1.00000	0.41465	0.38361	0.30443	0.25085	-0.17101	0.16296
	0.0	0.1244	0.0025	0.0180	0.1812	0.3662	0.2135
	60	15	60	60	30	30	60
K	K	WSOC	MG	CO2C	CA	PH	WAS
	1.00000	-0.42186	0.38289	0.25651	0.24675	-0.20372	0.14611
	0.0	0.0008	0.0025	0.3561	0.0574	0.1185	0.4410
	60	60	60	15	60	60	30
MG	MG	K	PH	CA	WSOC	TOTC	P
	1.00000	0.38289	-0.27940	0.25086	-0.22749	0.20519	0.16296
	0.0	0.0025	0.0306	0.0532	0.0805	0.1158	0.2135
	60	60	60	60	60	60	60
CA	CA	WDCL	PH	NH4N	TOTN	TOTC	MG
	1.00000	0.87595	-0.62585	0.30593	0.29496	0.25309	0.25086
	0.0	0.0001	0.0001	0.0174	0.0221	0.0510	0.0532
	60	30	60	60	60	60	60
PH	PH	WDCL	CA	MG	TOTN	NH4N	WAS
	1.00000	-0.76119	-0.62585	-0.27940	-0.24055	-0.23077	0.22188
	0.0	0.0001	0.0001	0.0306	0.0641	0.0761	0.2386
	60	30	60	60	60	60	30
NH4N	NH4N	TOTN	CO2C	CA	NO3N	WAS	PH
	1.00000	0.98745	-0.64194	0.30593	-0.29556	-0.26454	-0.23077
	0.0	0.0001	0.0099	0.0174	0.0219	0.1577	0.0761
	60	60	15	60	60	30	60
NO3N	NO3N	CO2C	WSOC	NH4N	WAS	TOTN	CA
	1.00000	0.45929	0.41735	-0.29556	0.28849	-0.14095	-0.13354
	0.0	0.0850	0.0009	0.0219	0.1221	0.2827	0.3091
	60	15	60	60	30	60	60

Table 11. (continued)

WSOC

WSOC	K	CO2C	NO3N	P	WDCL	MG
1.00000	-0.42186	0.42020	0.41735	0.38361	0.27880	-0.22749
0.0	0.0008	0.1189	0.0009	0.0025	0.1357	0.0805
60	60	15	60	60	30	60

CO2C

CO2C	NH4N	TOTN	NO3N	WSOC	P	WAS
1.00000	-0.64194	-0.50142	0.45929	0.42020	0.41465	-0.37069
0.0	0.0099	0.0569	0.0850	0.1189	0.1244	0.1738
15	15	15	15	15	15	15

TOTC

TOTC	CO2C	P	CA	MG	WAS	PH
1.00000	-0.35226	0.30443	0.25309	0.20519	0.11254	-0.09012
0.0	0.1978	0.0180	0.0510	0.1158	0.5538	0.4935
60	15	60	60	60	30	60

WAS

WAS	CO2C	WDCL	NO3N	NH4N	CA	PH
1.00000	-0.37069	-0.31358	0.28849	-0.26454	-0.23743	0.22188
0.0	0.1738	0.0915	0.1221	0.1577	0.2065	0.2386
30	15	30	30	30	30	30

WDCL

WDCL	CA	PH	WAS	WSOC	P	CO2C
1.00000	0.87595	-0.76119	-0.31358	0.27880	0.25085	0.20468
0.0	0.0001	0.0001	0.0915	0.1357	0.1812	0.4643
30	30	30	30	30	30	15

TOTN

TOTN	NH4N	CO2C	CA	PH	NO3N	WAS
1.00000	0.98745	-0.50142	0.29496	-0.24055	-0.14095	-0.10684
0.0	0.0001	0.0569	0.0221	0.0641	0.2827	0.5742
60	60	15	60	60	60	30

Table 12: Pearson correlation coefficients / prob > |R| under Ho: Rho=0 / number of observations, for each variable with seven most highly correlated variables, for Honeywood loam in Exp. 1

P

P	MG	WSOC	K	CO2C	NO3N	CA
1.00000	-0.44329	0.41264	-0.37671	-0.31915	0.24296	0.10612
0.0	0.0004	0.0011	0.0030	0.0856	0.0614	0.4197
60	60	60	60	30	60	60

K

K	P	PH	WSOC	NH4N	TOTN	NO3N
1.00000	-0.37671	-0.37315	-0.36697	0.36238	0.33734	-0.25402
0.0	0.0030	0.0033	0.0039	0.0044	0.0084	0.0502
60	60	60	60	60	60	60

MG

MG	WSOC	P	CO2C	TOTC	WAS	WDCL
1.00000	-0.50124	-0.44329	0.35210	-0.32523	0.28806	-0.28559
0.0	0.0001	0.0004	0.0564	0.0112	0.1227	0.1261
60	60	60	30	60	30	30

CA

CA	CO2C	WDCL	PH	WAS	NO3N	WSOC
1.00000	-0.48265	0.48000	-0.37946	-0.20111	-0.16464	0.15418
0.0	0.0069	0.0073	0.0028	0.2866	0.2087	0.2395
60	30	30	60	30	60	60

PH

PH	WDCL	WAS	CA	K	WSOC	CO2C
1.00000	-0.79362	0.62572	-0.37946	-0.37315	0.36061	0.18036
0.0	0.0001	0.0002	0.0028	0.0033	0.0046	0.3402
60	30	30	60	60	60	30

NH4N

NH4N	TOTN	WDCL	K	TOTC	NO3N	CA
1.00000	0.99131	0.56009	0.36238	-0.27558	-0.25724	0.11737
0.0	0.0001	0.0013	0.0044	0.0331	0.0472	0.3718
60	60	30	60	60	60	60

NO3N

NO3N	WDCL	NH4N	K	P	CO2C	CA
1.00000	-0.40222	-0.25724	-0.25402	0.24296	0.16671	-0.16464
0.0	0.0276	0.0472	0.0502	0.0614	0.3786	0.2087
60	30	60	60	60	30	60

Table 12. (continued)

WSOC

WSOC	MG	P	K	PH	TOTC	WDCL
1.00000	-0.50124	0.41264	-0.36697	0.36061	0.33325	0.29333
0.0	0.0001	0.0011	0.0039	0.0046	0.0093	0.1157
60	60	60	60	60	60	30

CO2C

CO2C	CA	MG	P	WSOC	PH	WDCL
1.00000	-0.48265	0.35210	-0.31915	-0.19070	0.18036	0.17841
0.0	0.0069	0.0564	0.0856	0.3128	0.3402	0.5247
30	30	30	30	30	30	15

TOTC

TOTC	WDCL	WAS	WSOC	MG	TOTN	NH4N
1.00000	0.58057	-0.46226	0.33325	-0.32523	-0.28346	-0.27558
0.0	0.0008	0.0101	0.0093	0.0112	0.0282	0.0331
60	30	30	60	60	60	60

WAS

WAS	PH	WDCL	TOTC	MG	WSOC	K
1.00000	0.62572	-0.59153	-0.46226	0.28806	-0.23371	0.22598
0.0	0.0002	0.0006	0.0101	0.1227	0.2139	0.2298
30	30	30	30	30	30	30

WDCL

WDCL	PH	WAS	TOTC	NH4N	CA	TOTN
1.00000	-0.79362	-0.59153	0.58057	0.56009	0.48000	0.43117
0.0	0.0001	0.0006	0.0008	0.0013	0.0073	0.0174
30	30	30	30	30	30	30

TOTN

TOTN	NH4N	WDCL	K	TOTC	NO3N	WAS
1.00000	0.99131	0.43117	0.33734	-0.28346	-0.12788	0.10233
0.0	0.0001	0.0174	0.0084	0.0282	0.3302	0.5905
60	60	30	60	60	60	30

Table 13: Pearson correlation coefficients / prob > |R| under Ho: Rho=0 / number of observations, for each variable with seven most highly correlated variables, for Brookston clay on day 1 in Exp. 1

P

P	K	TOTN	NH4N	TOTC	CA	MG
1.00000	-0.43704	0.25374	0.25356	-0.12315	0.09145	0.06798
0.0	0.1033	0.3615	0.3618	0.6619	0.7458	0.8098
15	15	15	15	15	15	15

K

K	P	WSOC	NH4N	TOTN	TOTC	PH
1.00000	-0.43704	0.31017	-0.26130	-0.26126	0.24562	-0.14038
0.0	0.1033	0.2605	0.3469	0.3469	0.3776	0.6178
15	15	15	15	15	15	15

MG

MG	CA	TOTC	WSOC	PH	NH4N	TOTN
1.00000	-0.49347	-0.41449	0.18224	0.15628	-0.15545	-0.15464
0.0	0.0616	0.1245	0.5157	0.5781	0.5801	0.5821
15	15	15	15	15	15	15

CA

CA	MG	TOTC	TOTN	NH4N	PH	P
1.00000	-0.49347	0.35178	0.26303	0.26276	0.17073	0.09145
0.0	0.0616	0.1985	0.3436	0.3441	0.5429	0.7458
15	15	15	15	15	15	15

PH

PH	TOTN	NH4N	WSOC	TOTC	CA	MG
1.00000	0.73246	0.73212	0.61467	-0.22821	0.17073	0.15628
0.0	0.0019	0.0019	0.0148	0.4133	0.5429	0.5781
15	15	15	15	15	15	15

NH4N

NH4N	TOTN	PH	CA	K	P	WSOC
1.00000	0.99998	0.73212	0.26276	-0.26130	0.25356	0.24329
0.0	0.0001	0.0019	0.3441	0.3469	0.3618	0.3822
15	15	15	15	15	15	15

NO3N

NO3N	TOTC	WSOC	MG	PH	CA	P
1.00000	-0.69588	0.30217	0.13258	0.07635	0.05087	0.03656
0.0	0.0040	0.2737	0.6376	0.7868	0.8571	0.8971
15	15	15	15	15	15	15

Table 13. (continued)

WSOC

WSOC	PH	TOTC	K	NO3N	TOTN	NH4N
1.00000	0.61467	-0.47698	0.31017	0.30217	0.24506	0.24329
0.0	0.0148	0.0722	0.2605	0.2737	0.3787	0.3822
15	15	15	15	15	15	15

CO2C

TOTN	WDCL	WAS	TOTC	CO2C	WSOC	NO3N
.	.	.	.	.	.	.
0	0	0	0	0	0	0

TOTC

TOTC	NO3N	WSOC	MG	CA	K	PH
1.00000	-0.69588	-0.47698	-0.41449	0.35178	0.24562	-0.22821
0.0	0.0040	0.0722	0.1245	0.1985	0.3776	0.4133
15	15	15	15	15	15	15

WAS

TOTN	WDCL	WAS	TOTC	CO2C	WSOC	NO3N
.	.	.	.	.	.	.
0	0	0	0	0	0	0

WDCL

TOTN	WDCL	WAS	TOTC	CO2C	WSOC	NO3N
.	.	.	.	.	.	.
0	0	0	0	0	0	0

TOTN

TOTN	NH4N	PH	CA	K	P	WSOC
1.00000	0.99998	0.73246	0.26303	-0.26126	0.25374	0.24506
0.0	0.0001	0.0019	0.3436	0.3469	0.3615	0.3787
15	15	15	15	15	15	15

Table 14: Pearson correlation coefficients / prob > |R| under Ho: Rho=0 / number of observations, for each variable with seven most highly correlated variables, for Gobles loam on day 1 in Exp. 1

	P	K	MG	TOTC	CA	TOTN	NH4N
P	1.00000	0.53655	-0.35222	-0.32048	-0.24836	0.08788	0.08098
	0.0	0.0392	0.1979	0.2442	0.3721	0.7555	0.7742
	15	15	15	15	15	15	15
K	1.00000	0.62312	0.53655	-0.46139	-0.32423	-0.30431	-0.17416
	0.0	0.0131	0.0392	0.0834	0.2384	0.2701	0.5347
	15	15	15	15	15	15	15
MG	1.00000	-0.68059	-0.67852	0.57309	-0.55755	0.50577	-0.35222
	0.0	0.0052	0.0054	0.0255	0.0308	0.0544	0.1979
	15	15	15	15	15	15	15
CA	1.00000	0.27626	-0.24836	0.11107	0.09872	0.08874	-0.06490
	0.0	0.3189	0.3721	0.6935	0.7263	0.7532	0.8182
	15	15	15	15	15	15	15
PH	1.00000	0.85472	0.84660	-0.83261	-0.55755	-0.47486	-0.46139
	0.0	0.0001	0.0001	0.0001	0.0308	0.0737	0.0834
	15	15	15	15	15	15	15
NH4N	1.00000	0.99948	0.85472	-0.81029	-0.67852	-0.61137	0.51650
	0.0	0.0001	0.0001	0.0002	0.0054	0.0155	0.0487
	15	15	15	15	15	15	15
NO3N	1.00000	-0.83261	-0.81029	-0.79106	0.62312	0.50577	0.48824
	0.0	0.0001	0.0002	0.0004	0.0131	0.0544	0.0648
	15	15	15	15	15	15	15

Table 14. (continued)

WSOC

WSOC	TOTN	NH4N	PH	NO3N	TOTC	K
1.00000	0.52164	0.51650	0.42055	-0.31997	-0.18048	-0.17416
0.0	0.0461	0.0487	0.1185	0.2450	0.5198	0.5347
15	15	15	15	15	15	15

CO2C

TOTN	WDCL	WAS	TOTC	CO2C	WSOC	NO3N
.	.	.	.	.	.	.
0	0	0	0	0	0	0

TOTC

TOTC	TOTN	NH4N	MG	NO3N	PH	P
1.00000	-0.61144	-0.61137	0.57309	0.48824	-0.47486	-0.32048
0.0	0,0154	0.0155	0.0255	0.0648	0.0737	0.2442
15	15	15	15	15	15	15

WAS

TOTN	WDCL	WAS	TOTC	CO2C	WSOC	NO3N
.	.	.	.	.	.	.
0	0	0	0	0	0	0

WDCL

TOTN	WDCL	WAS	TOTC	CO2C	WSOC	NO3N
.	.	.	.	.	.	.
0	0	0	0	0	0	0

TOTN

TOTN	NH4N	PH	NO3N	MG	TOTC	WSOC
1.00000	0.99948	0.84660	-0.79106	-0.68059	-0.61144	0.52164
0.0	0.0001	0.0001	0.0004	0.0052	0.0154	0.0461
15	15	15	15	15	15	15

Table 15: Pearson correlation coefficients / prob > |R| under Ho: Rho=0 / number of observations, for each variable with seven most highly correlated variables, for Honeywood loam on day 1 in Exp. 1

P

P	MG	WSOC	K	NO3N	TOTN	NH4N
1.00000	-0.47083	0.42190	0.34039	0.23214	0.22724	0.21583
0.0	0.0765	0.1172	0.2144	0.4051	0.4154	0.4398
15	15	15	15	15	15	15

K

K	P	NH4N	TOTN	MG	NO3N	WSOC
1.00000	0.34039	0.17271	0.16751	-0.15023	-0.14685	-0.14064
0.0	0.2144	0.5382	0.5507	0.5931	0.6015	0.6171
15	15	15	15	15	15	15

MG

MG	NO3N	P	TOTC	CA	K	TOTN
1.00000	-0.67539	-0.47083	-0.21770	-0.15076	-0.15023	-0.11686
0.0	0.0057	0.0765	0.4357	0.5917	0.5931	0.6783
15	15	15	15	15	15	15

CA

CA	WSOC	P	MG	NH4N	TOTN	PH
1.00000	-0.38346	-0.19328	-0.15076	-0.09522	-0.09460	-0.03747
0.0	0.1583	0.4901	0.5917	0.7357	0.7374	0.8945
15	15	15	15	15	15	15

PH

PH	NH4N	TOTN	TOTC	WSOC	NO3N	K
1.00000	0.83951	0.83439	-0.46235	0.32369	-0.24555	-0.08912
0.0	0.0001	0.0001	0.0827	0.2392	0.3777	0.7521
15	15	15	15	15	15	15

NH4N

NH4N	TOTN	PH	WSOC	TOTC	P	K
1.00000	0.99910	0.83951	0.42569	-0.40615	0.21583	0.17271
0.0	0.0001	0.0001	0.1136	0.1330	0.4398	0.5382
15	15	15	15	15	15	15

NO3N

NO3N	MG	PH	WSOC	P	TOTC	NH4N
1.00000	-0.67539	-0.24555	0.23766	0.23214	0.17963	-0.17185
0.0	0.0057	0.3777	0.3937	0.4051	0.5218	0.5403
15	15	15	15	15	15	15

Table 15. (continued)

WSOC

WSOC	TOTN	NH4N	P	CA	PH	NO3N
1.00000	0.43871	0.42569	0.42190	-0.38346	0.32369	0.23766
0.0	0.1019	0.1136	0.1172	0.1583	0.2392	0.3937
15	15	15	15	15	15	15

CO2C

TOTN	WDCL	WAS	TOTC	CO2C	WSOC	NO3N
.	.	.	.	.	.	.
0	0	0	0	0	0	0

TOTC

TOTC	PH	NH4N	TOTN	MG	P	WSOC
1.00000	-0.46235	-0.40615	-0.40105	-0.21770	0.18420	-0.18122
0.0	0.0827	0.1330	0.1385	0.4357	0.5111	0.5180
15	15	15	15	15	15	15

WAS

TOTN	WDCL	WAS	TOTC	CO2C	WSOC	NO3N
.	.	.	.	.	.	.
0	0	0	0	0	0	0

WDCL

TOTN	WDCL	WAS	TOTC	CO2C	WSOC	NO3N
.	.	.	.	.	.	.
0	0	0	0	0	0	0

TOTN

TOTN	NH4N	PH	WSOC	TOTC	P	K
1.00000	0.99910	0.83439	0.43871	-0.40105	0.22724	0.16751
0.0	0.0001	0.0001	0.1019	0.1385	0.4154	0.5507
15	15	15	15	15	15	15

Table 16: Pearson correlation coefficients / prob > |R| under Ho: Rho=0 / number of observations, for each variable with seven most highly correlated variables, for Honeywood loam in Exp. 2

CO2C

CO2C	WSOC	WDCL	PH	NO3N	WAS	NH4N
1.00000	0.74728	0.73491	0.69679	-0.61069	-0.57742	0.34343
0.0	0.0001	0.0001	0.0001	0.0001	0.0008	0.0209
45	45	30	45	45	30	45

NH4N

NH4N	TOTN	PH	WDCL	WSOC	WAS	CO2C
1.00000	0.87828	0.76022	0.58312	0.37013	-0.34882	0.34343
0.0	0.0001	0.0001	0.0007	0.0123	0.0589	0.0209
45	45	45	30	45	30	45

NO3N

NO3N	WAS	PH	WSOC	WDCL	CO2C	TOTN
1.00000	0.81193	-0.75316	-0.72792	-0.66793	-0.61069	0.24968
0.0	0.0001	0.0001	0.0001	0.0001	0.0001	0.0981
45	30	45	45	30	45	45

PH

PH	WDCL	NH4N	NO3N	WSOC	WAS	CO2C
1.00000	0.86796	0.76022	-0.75316	0.75213	-0.73064	0.69679
0.0	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001
45	30	45	45	45	30	45

WSOC

WSOC	PH	CO2C	NO3N	WDCL	WAS	NH4N
1.00000	0.75213	0.74728	-0.72792	0.62060	-0.61354	0.37013
0.0	0.0001	0.0001	0.0001	0.0003	0.0003	0.0123
45	45	45	45	30	30	45

WAS

WAS	WDCL	NO3N	PH	WSOC	CO2C	NH4N
1.00000	-0.86216	0.81193	-0.73064	-0.61354	-0.57742	-0.34882
0.0	0.0001	0.0001	0.0001	0.0003	0.0008	0.0589
30	30	30	30	30	30	30

WDCL

WDCL	PH	WAS	CO2C	NO3N	WSOC	NH4N
1.00000	0.86796	-0.86216	0.73491	-0.66793	0.62060	0.58312
0.0	0.0001	0.0001	0.0001	0.0001	0.0003	0.0007
30	30	30	30	30	30	30

TOTN

TOTN	NH4N	PH	NO3N	WDCL	WAS	CO2C
1.00000	0.87828	0.38771	0.24968	0.21688	0.07428	0.04181
0.0	0.0001	0.0085	0.0981	0.2496	0.6965	0.7851
45	45	45	45	30	30	45

Table 17: Pearson correlation coefficients / prob > |R| under Ho: Rho=0 / number of observations, for each variable with seven most highly correlated variables, for Honeywood loam on day 1 in Exp. 2

CO2C

CO2C	NO3N	NH4N	PH	TOTN	WSOC	WAS
1.00000	0.64024	-0.15994	-0.14955	-0.14611	0.04421	.
0.0	0.0101	0.5691	0.5947	0.6034	0.8757	
15	15	15	15	15	15	0

NH4N

NH4N	TOTN	PH	NO3N	WSOC	CO2C	WAS
1.00000	0.99976	0.98987	-0.44316	-0.30056	-0.15994	.
0.0	0.0001	0.0001	0.0980	0.2764	0.5691	
15	15	15	15	15	15	0

NO3N

NO3N	CO2C	PH	NH4N	TOTN	WSOC	WAS
1.00000	0.64024	-0.47609	-0.44316	-0.42360	-0.06007	.
0.0	0.0101	0.0728	0.0980	0.1156	0.8316	
15	15	15	15	15	15	0

PH

PH	NH4N	TOTN	NO3N	WSOC	CO2C	WAS
1.00000	0.98987	0.98873	-0.47609	-0.23026	-0.14955	.
0.0	0.0001	0.0001	0.0728	0.4090	0.5947	
15	15	15	15	15	15	0

WSOC

WSOC	TOTN	NH4N	PH	NO3N	CO2C	WAS
1.00000	-0.30517	-0.30056	-0.23026	-0.06007	0.04421	.
0.0	0.2687	0.2764	0.4090	0.8316	0.8757	
15	15	15	15	15	15	0

WAS

TOTN	WDCL	WAS	WSOC	PH	NO3N	NH4N
.	.	.	.	.	.	.
0	0	0	0	0	0	0

WDCL

TOTN	WDCL	WAS	WSOC	PH	NO3N	NH4N
.	.	.	.	.	.	.
0	0	0	0	0	0	0

TOTN

TOTN	NH4N	PH	NO3N	WSOC	CO2C	WAS
1.00000	0.99976	0.98873	-0.42360	-0.30517	-0.14611	.
0.0	0.0001	0.0001	0.1156	0.2687	0.6034	
15	15	15	15	15	15	0

Table 18: Pearson correlation coefficients / prob > |R| under Ho: Rho=0 / number of observations, for each variable with seven most highly correlated variables, for Honeywood loam on day 7 in Exp. 2

CO2C							
	CO2C	TOTN	NH4N	PH	WDCL	NO3N	WSOC
	1.00000	0.82576	0.79378	0.71707	0.36733	0.32427	0.32050
	0.0	0.0001	0.0004	0.0026	0.1780	0.2383	0.2442
NH4N							
	NH4N	TOTN	PH	CO2C	WDCL	WSOC	WAS
	1.00000	0.98086	0.92867	0.79378	0.55614	0.34363	-0.11652
	0.0	0.0001	0.0001	0.0004	0.0313	0.2098	0.6792
NO3N							
	NO3N	WDCL	CO2C	TOTN	WAS	PH	WSOC
	1.00000	-0.36931	0.32427	0.29665	0.23205	-0.22668	0.20604
	0.0	0.1755	0.2383	0.2830	0.4053	0.4165	0.4613
PH							
	PH	NH4N	TOTN	CO2C	WDCL	WSOC	NO3N
	1.00000	0.92867	0.84741	0.71707	0.62196	0.25665	-0.22668
	0.0	0.0001	0.0001	0.0026	0.0133	0.3558	0.4165
WSOC							
	WSOC	TOTN	NH4N	CO2C	PH	NO3N	WAS
	1.00000	0.37033	0.34363	0.32050	0.25665	0.20604	0.14963
	0.0	0.1742	0.2098	0.2442	0.3558	0.4613	0.5945
WAS							
	WAS	WDCL	NO3N	WSOC	PH	NH4N	TOTN
	1.00000	-0.64651	0.23205	0.14963	-0.14854	-0.11652	-0.06645
	0.0	0.0092	0.4053	0.5945	0.5973	0.6792	0.8140
WDCL							
	WDCL	WAS	PH	NH4N	TOTN	NO3N	CO2C
	1.00000	-0.64651	0.62196	0.55614	0.46174	-0.36931	0.36733
	0.0	0.0092	0.0133	0.0313	0.0832	0.1755	0.1780
TOTN							
	TOTN	NH4N	PH	CO2C	WDCL	WSOC	NO3N
	1.00000	0.98086	0.84741	0.82576	0.46174	0.37033	0.29665
	0.0	0.0001	0.0001	0.0001	0.0832	0.1742	0.2830

Table 19: Pearson correlation coefficients / prob > |R| under Ho: Rho=0 / number of observations, for each variable with seven most highly correlated variables, for Honeywood loam on day 28 in Exp. 2

CO2C						
CO2C	NO3N	WDCL	TOTN	WSOC	WAS	PH
1.00000	0.52991	0.29329	0.27546	-0.24180	0.17805	0.07505
0.0	0.0422	0.2887	0.3204	0.3853	0.5255	0.7904

NH4N						
NH4N	TOTN	NO3N	WAS	WDCL	PH	WSOC
1.00000	0.95688	0.80770	0.66869	-0.45015	0.13842	-0.10594
0.0	0.0001	0.0003	0.0064	0.0922	0.6227	0.7071

NO3N						
NO3N	TOTN	NH4N	WAS	CO2C	WSOC	PH
1.00000	0.94414	0.80770	0.70317	0.52991	-0.17171	0.14041
0.0	0.0001	0.0003	0.0035	0.0422	0.5406	0.6177

PH						
PH	WAS	WDCL	WSOC	TOTN	NO3N	NH4N
1.00000	0.53190	-0.38672	-0.25834	0.14655	0.14041	0.13842
0.0	0.0413	0.1545	0.3526	0.6023	0.6177	0.6227

WSOC						
WSOC	PH	WAS	CO2C	NO3N	TOTN	NH4N
1.00000	-0.25834	-0.24350	-0.24180	-0.17171	-0.14381	-0.10594
0.0	0.3526	0.3818	0.3853	0.5406	0.6091	0.7071

WAS						
WAS	TOTN	NO3N	NH4N	PH	WDCL	WSOC
1.00000	0.72020	0.70317	0.66869	0.53190	-0.40918	-0.24350
0.0	0.0025	0.0035	0.0064	0.0413	0.1299	0.3818

WDCL						
WDCL	NH4N	WAS	PH	CO2C	TOTN	NO3N
1.00000	-0.45015	-0.40918	-0.38672	0.29329	-0.29285	-0.08372
0.0	0.0922	0.1299	0.1545	0.2887	0.2895	0.7668

TOTN						
TOTN	NH4N	NO3N	WAS	WDCL	CO2C	PH
1.00000	0.95688	0.94414	0.72020	-0.29285	0.27546	0.14655
0.0	0.0001	0.0001	0.0025	0.2895	0.3204	0.6023

APPENDIX B

MAP 1 AND FIGURES 1 TO 23

Map 1: Location of Sample Sites

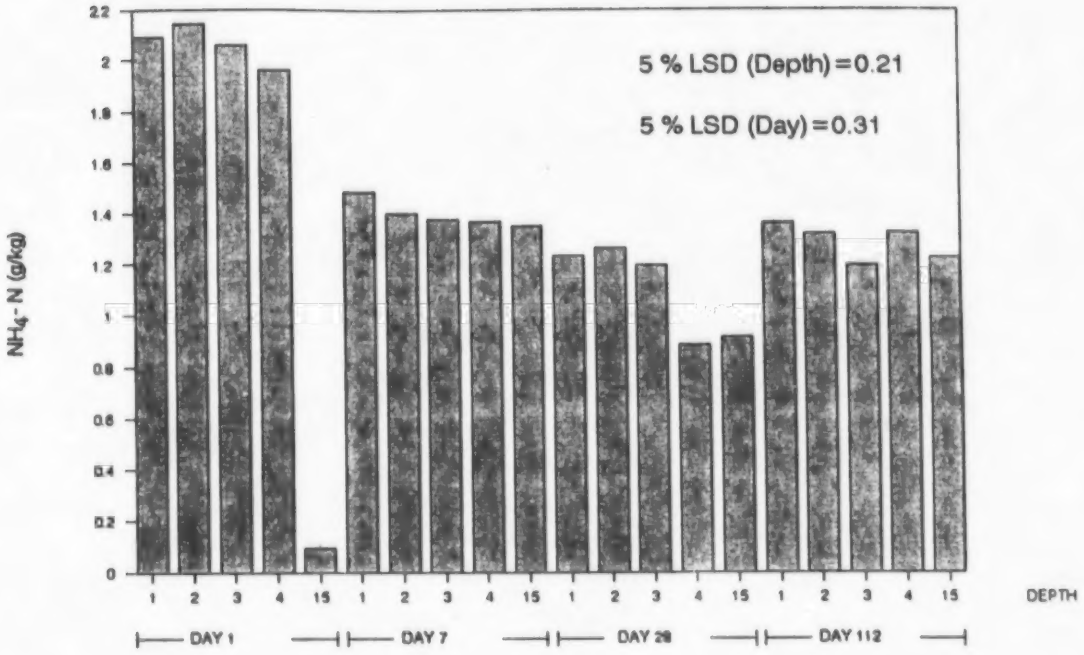

Figure 1. Exhangeable ammonium-N, averaged over soils, in Exp. 1.

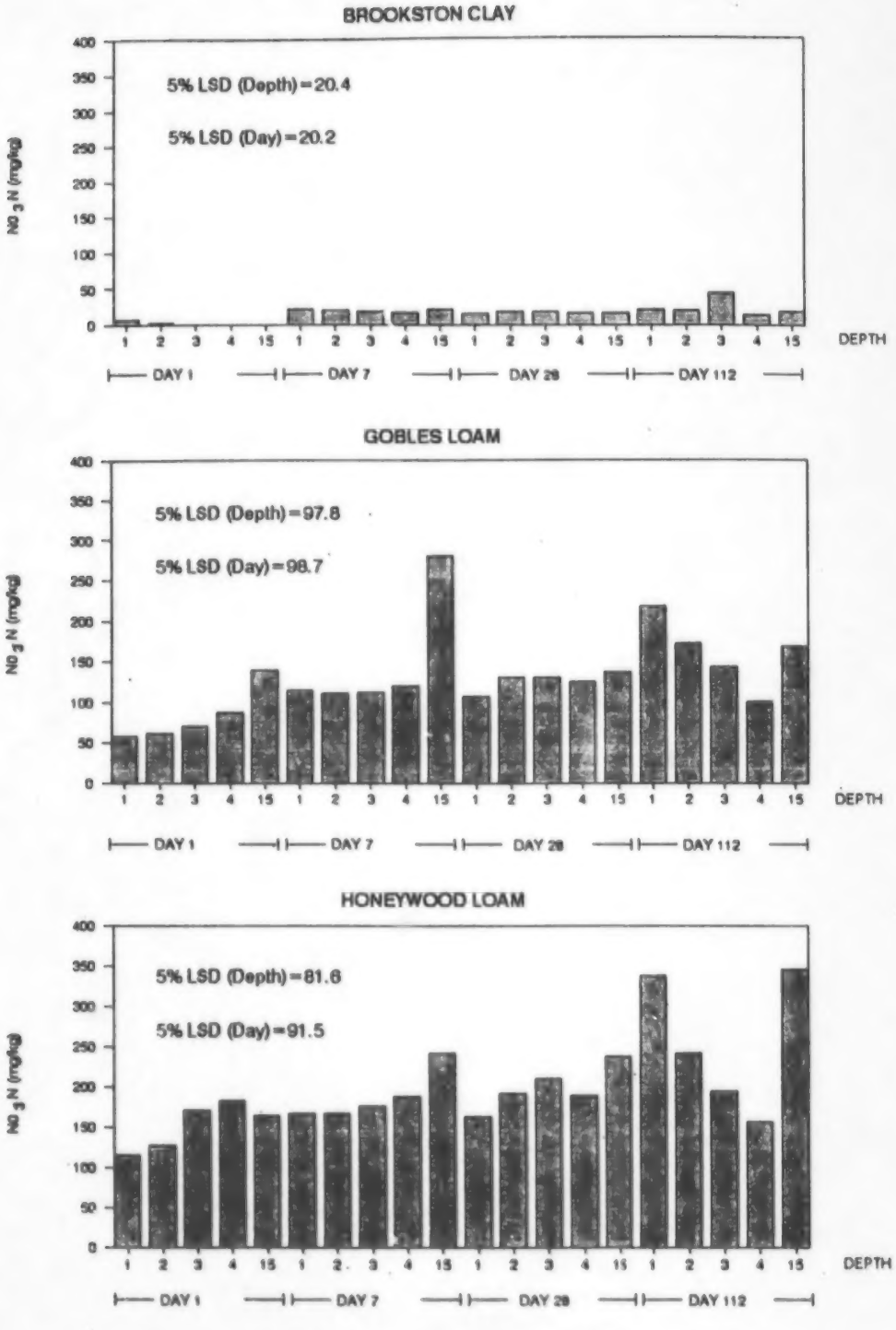

Figure 2. Nitrate-N in each soil in Exp. 1.

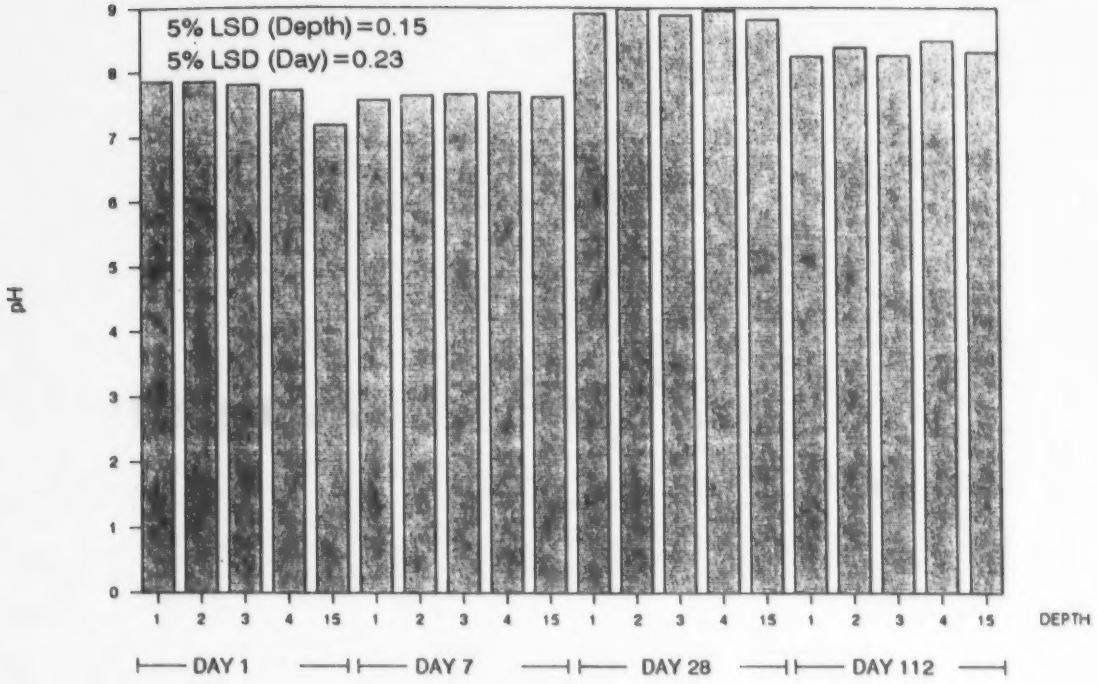

Figure 3. Soil pH averaged over three soils in Exp.1

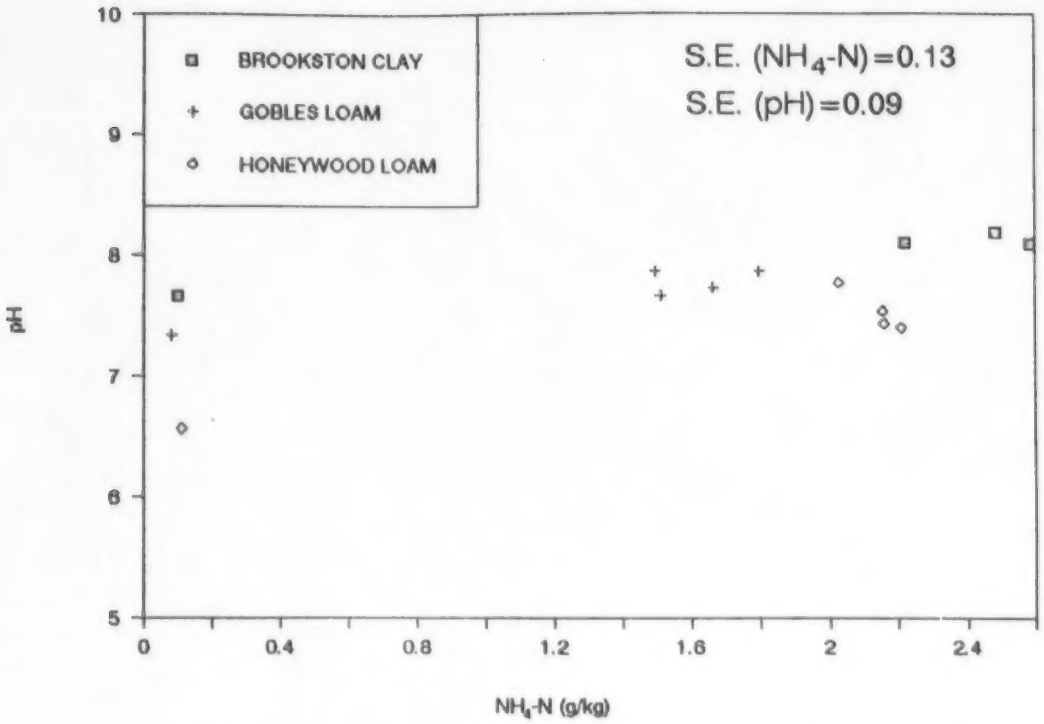

Figure 4. Plot of pH versus NH_4-N means from each depth on Day 1 in Exp. 1.

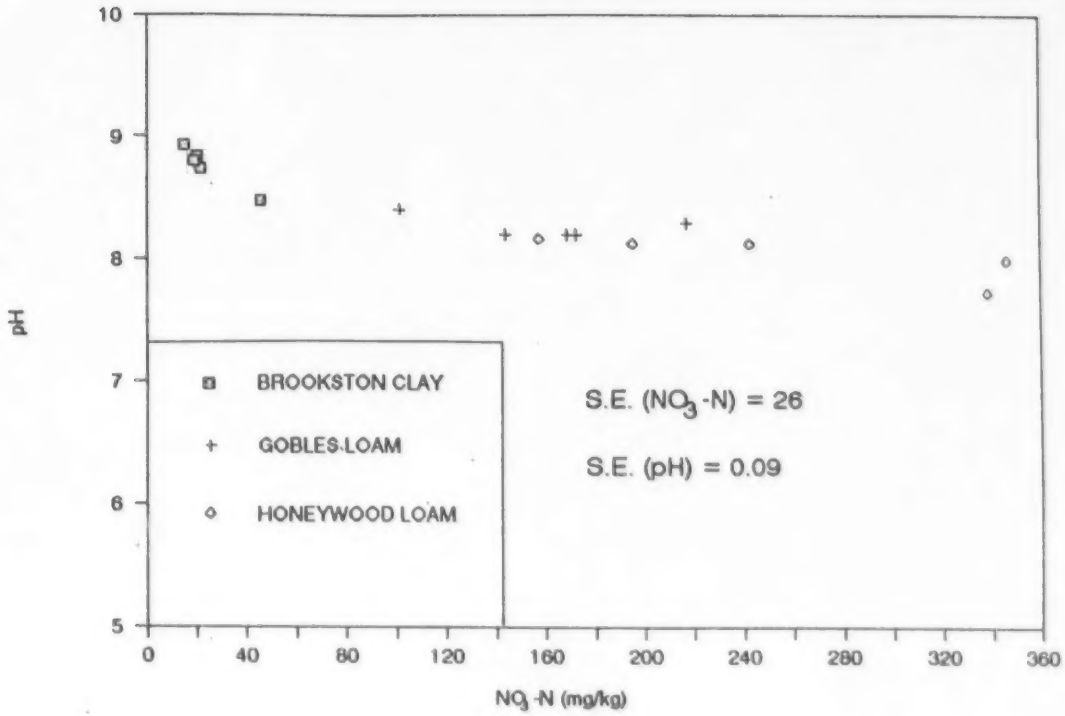

Figure 5. Plot of pH versus N0 $_3$N means from each depth on Day 112 in Exp. 1.

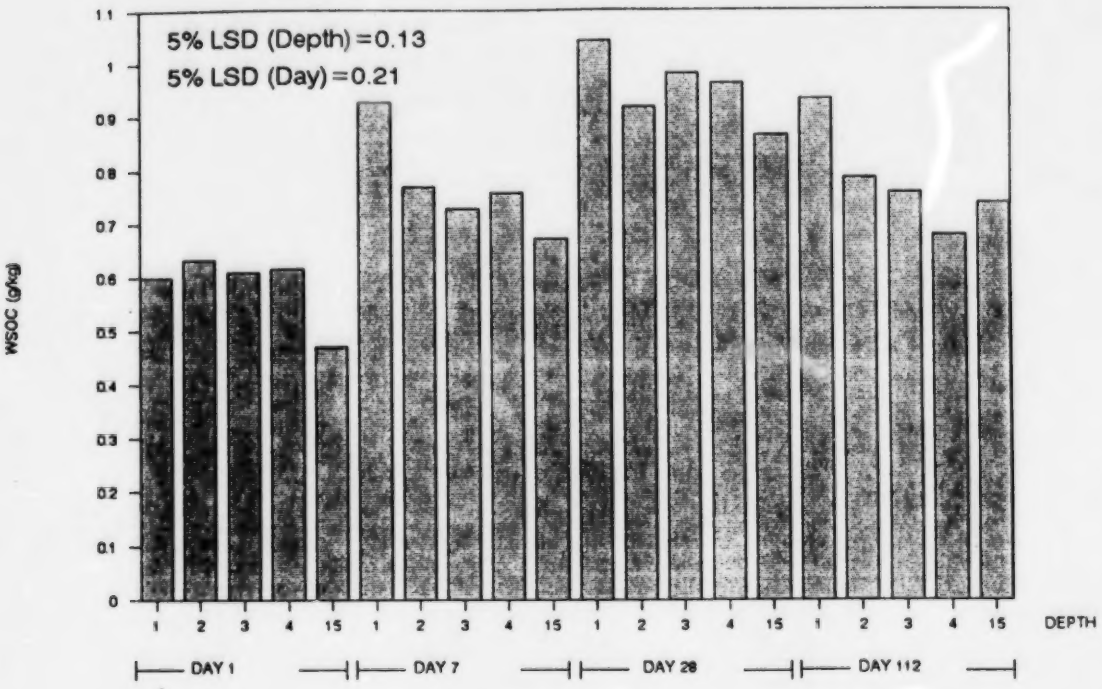

Figure 6. Water soluble organic C, averaged over soils in Exp. 1.

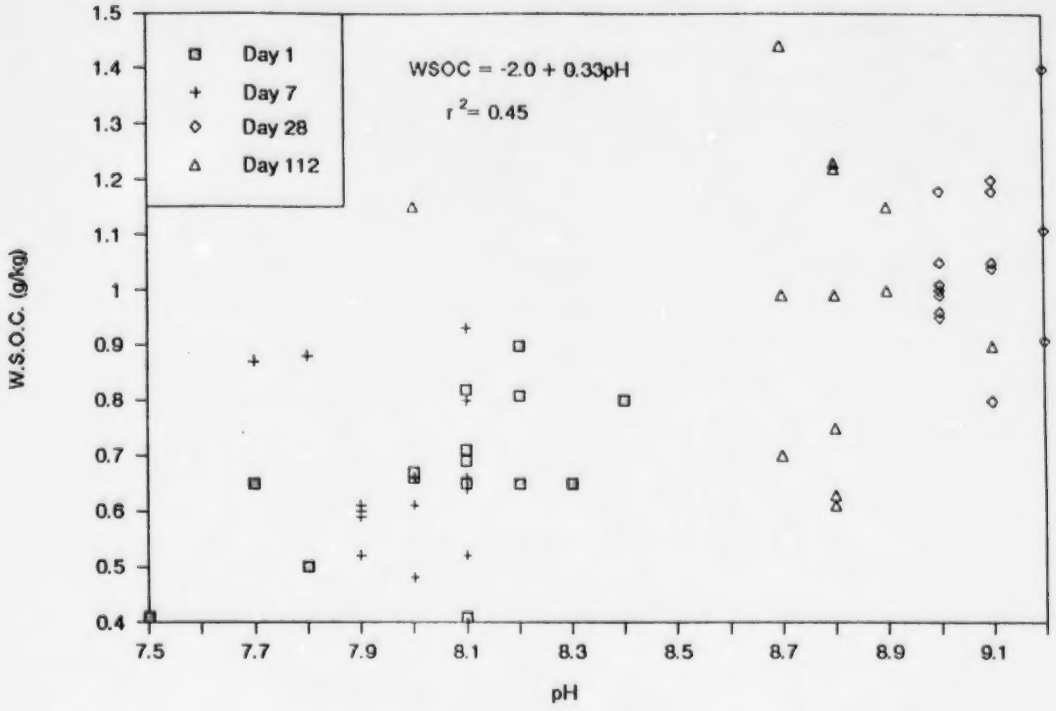

Figure 7. Plot and linear regression of water soluble organic C versus pH for Brookston clay in Exp. 1.

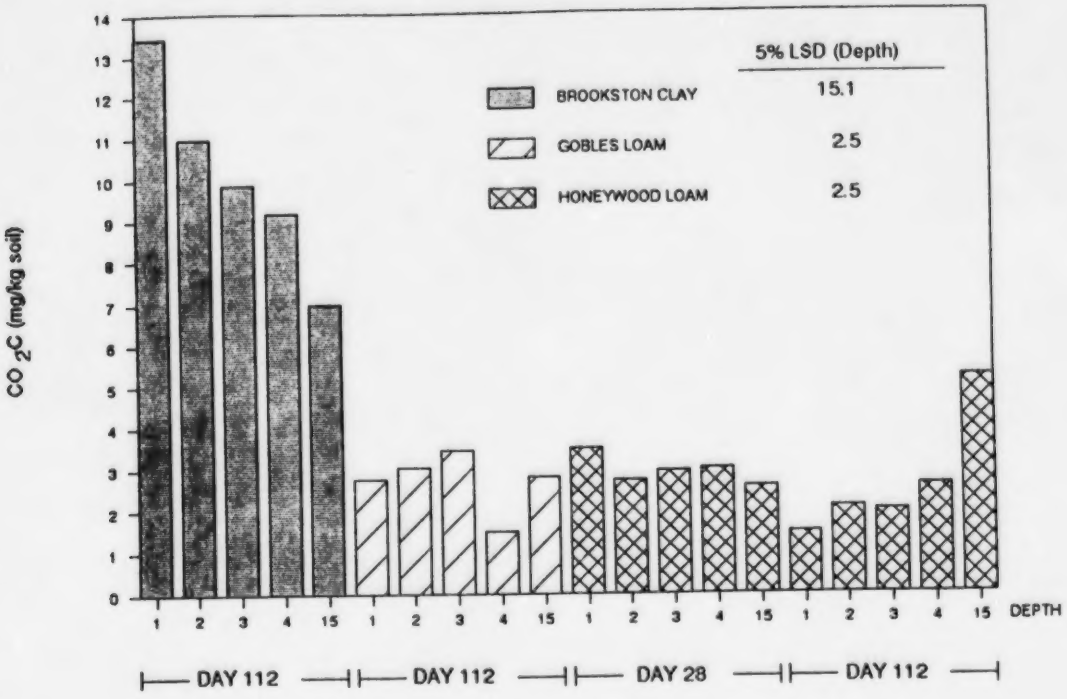

Figure 8. Production of $C0_2$-C by soils in Exp. 1.

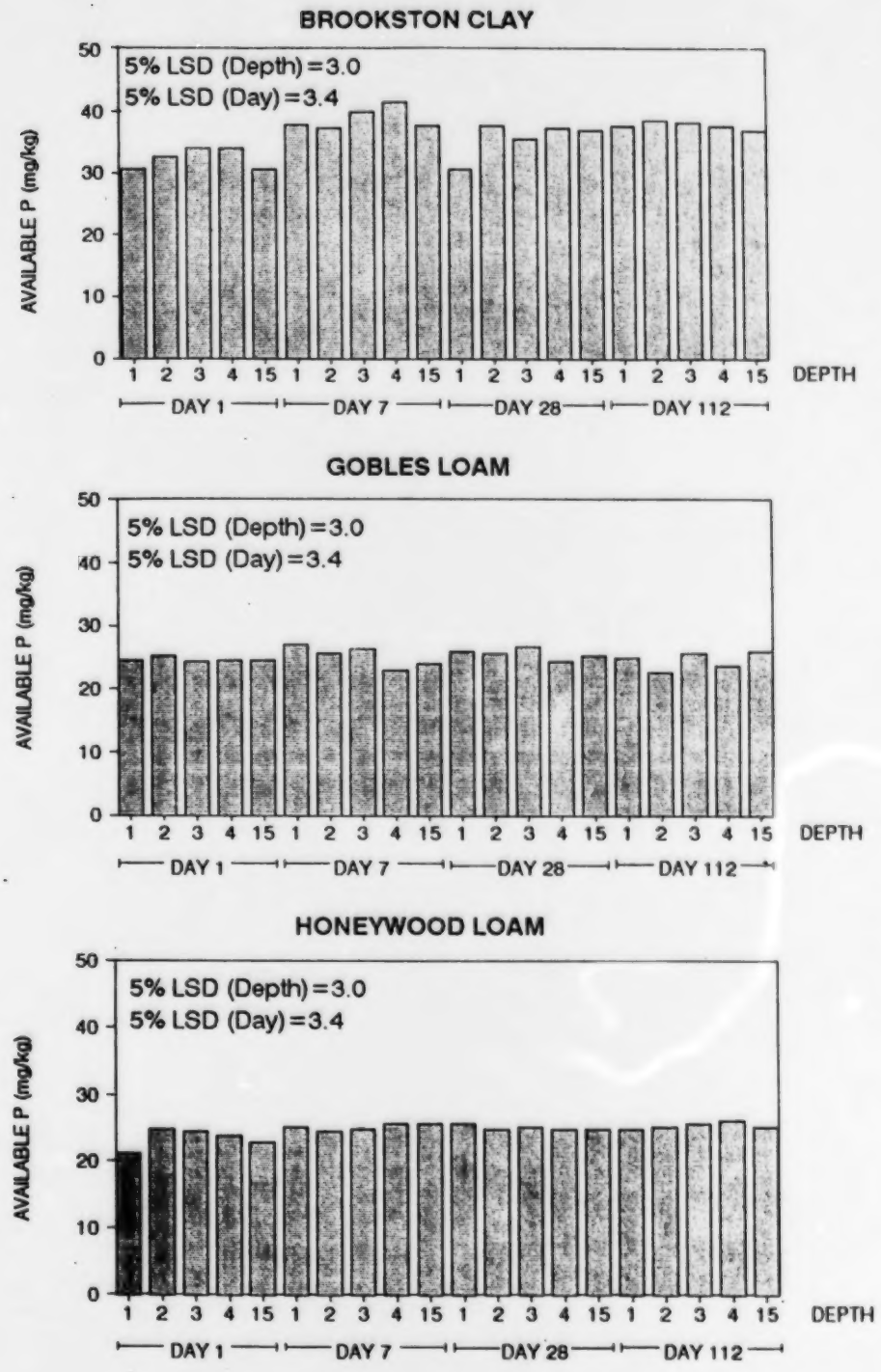

Figure 9. Plant-available P in soils from Exp. 1.

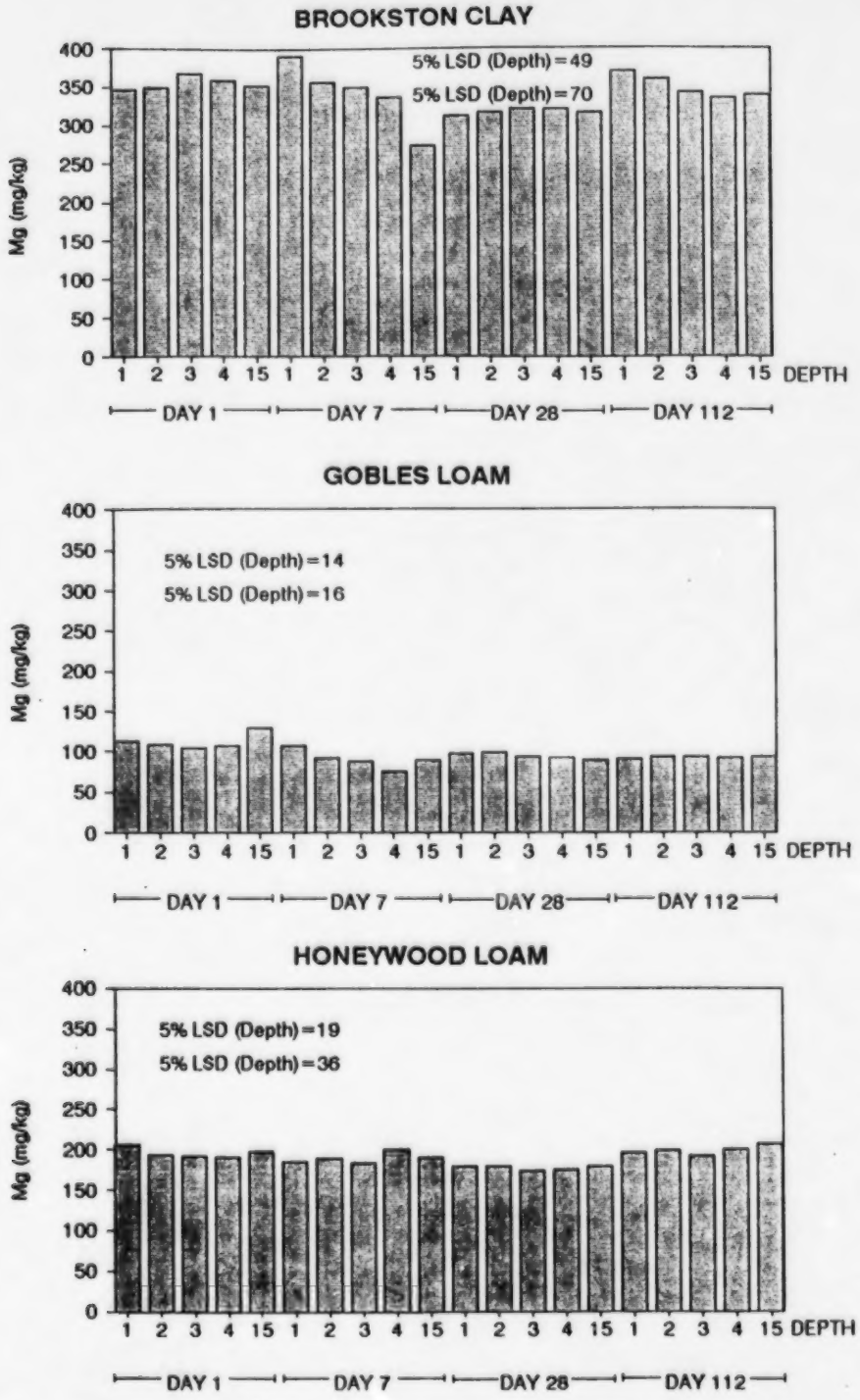

Figure 10. Exchangeable Mg in soils from Exp. 1.

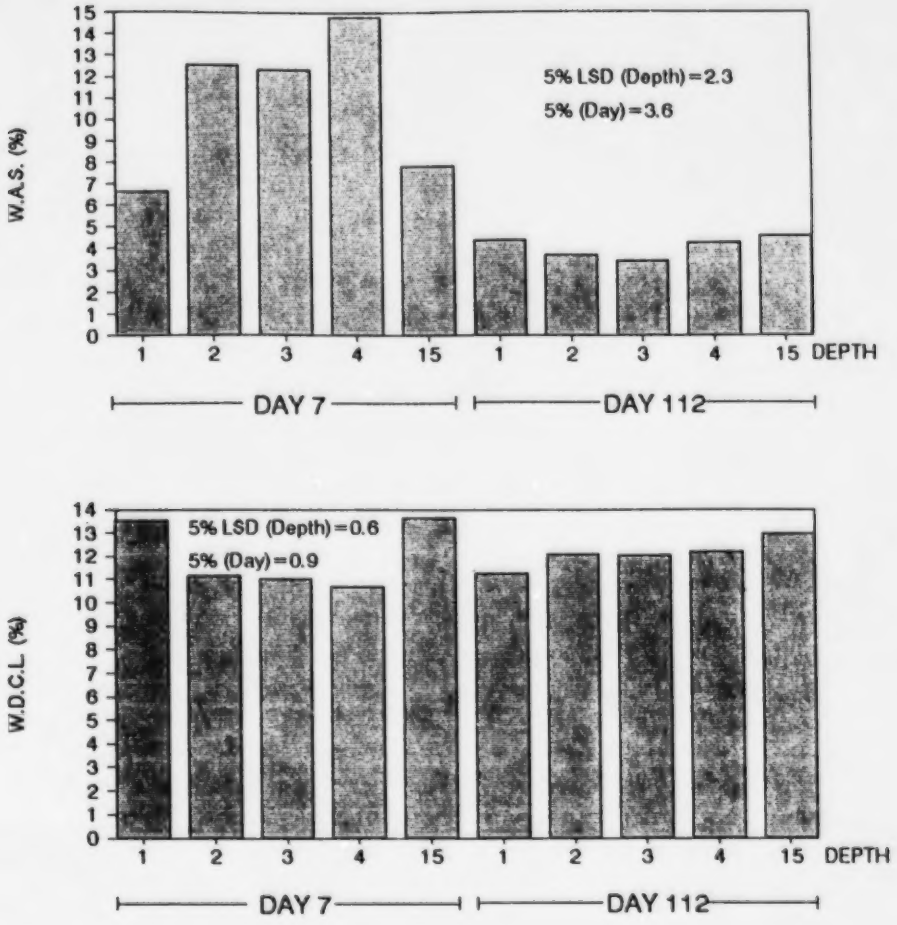

Figure 11. Wet aggregate stability (WAS) and water-dispersible clay (WDCL) of Brookston clay in Exp. 1.

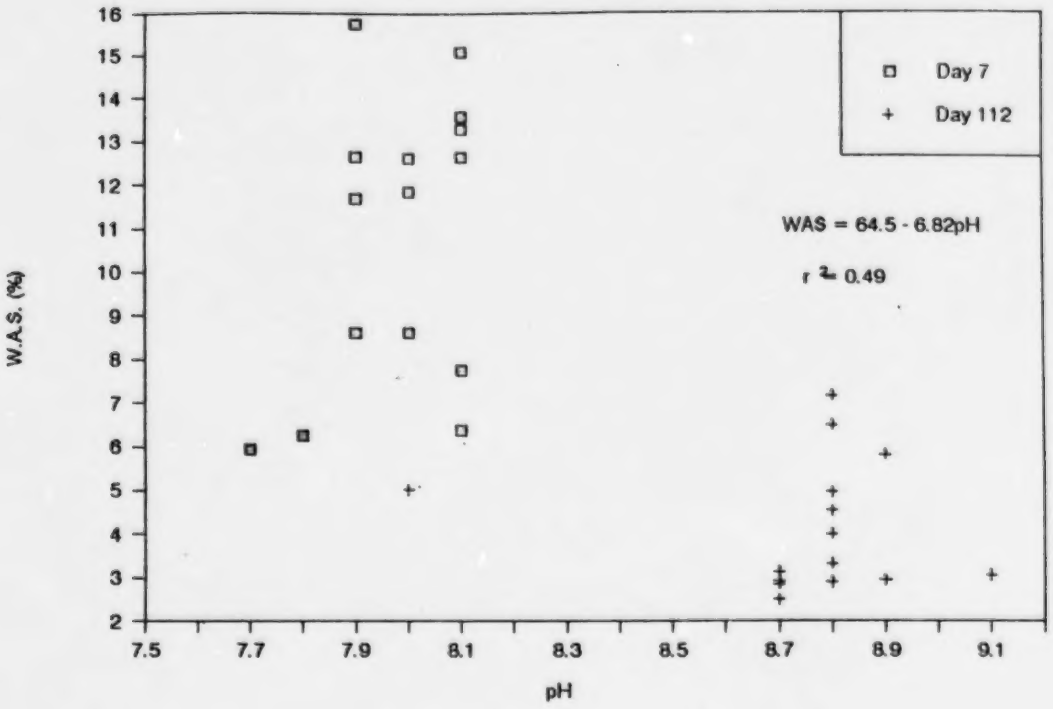

Figure 12. Plot and linear regression of wet aggregate stability versus pH for Brookston clay in Exp 1.

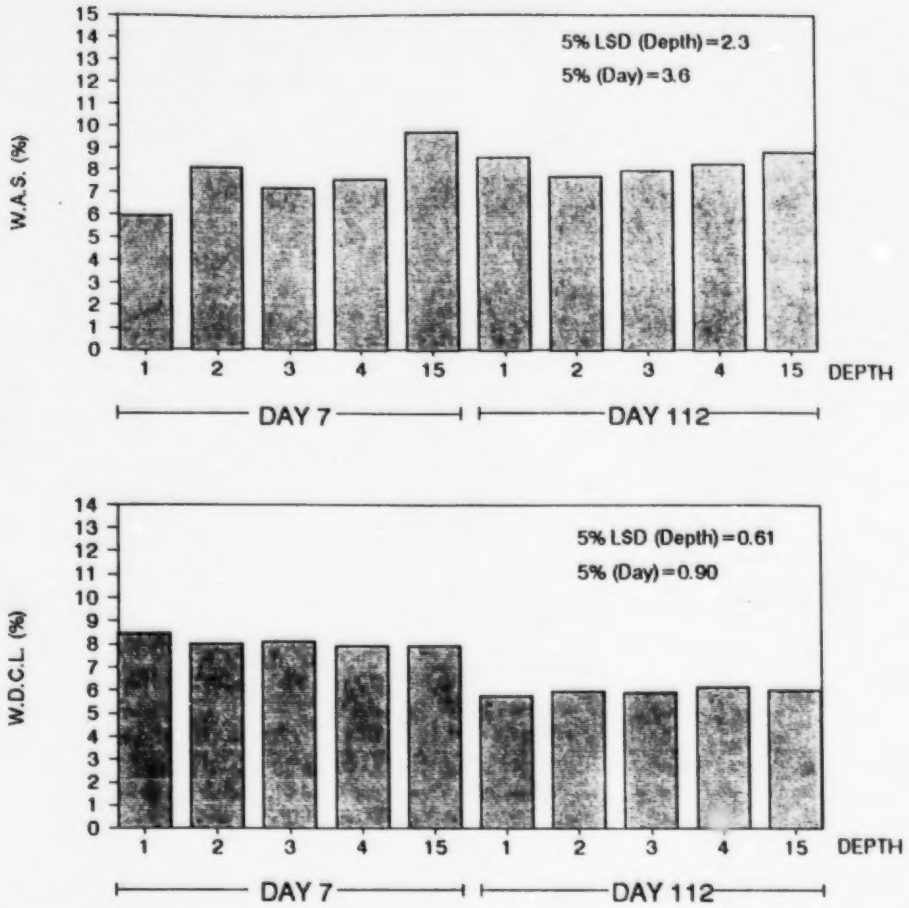

Figure 13. Wet aggregate stability and water-dispersible clay of Gobles loam in Exp. 1.

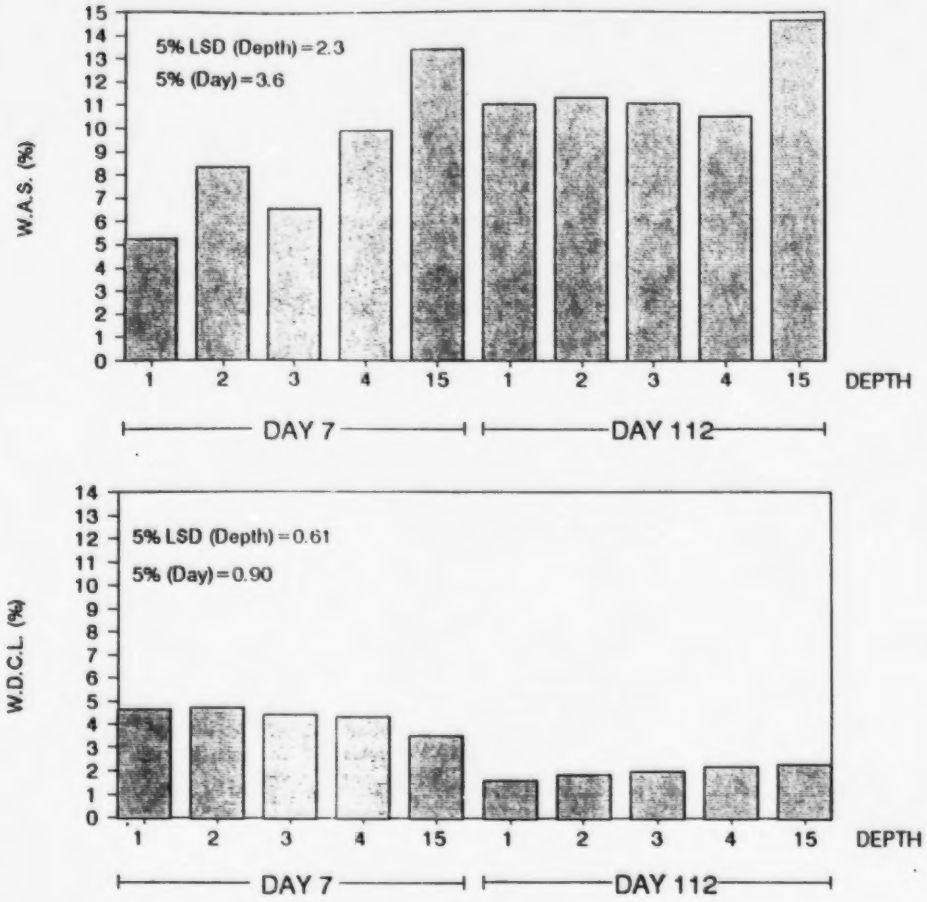

Figure 14. Wet aggregate stability and water dispersible clay of Honeywood loam in Exp. 1.

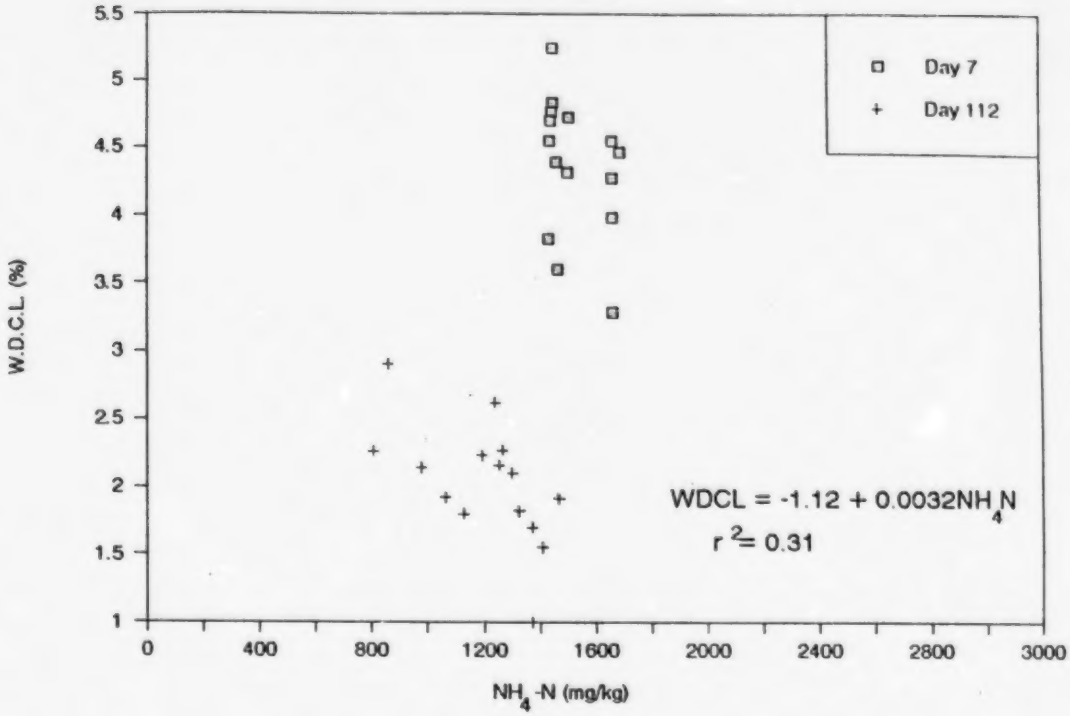

Figure 15. Plot and linear regression of water dispersible clay versus NH_4-N for the Honeywood loam in Exp. 1.

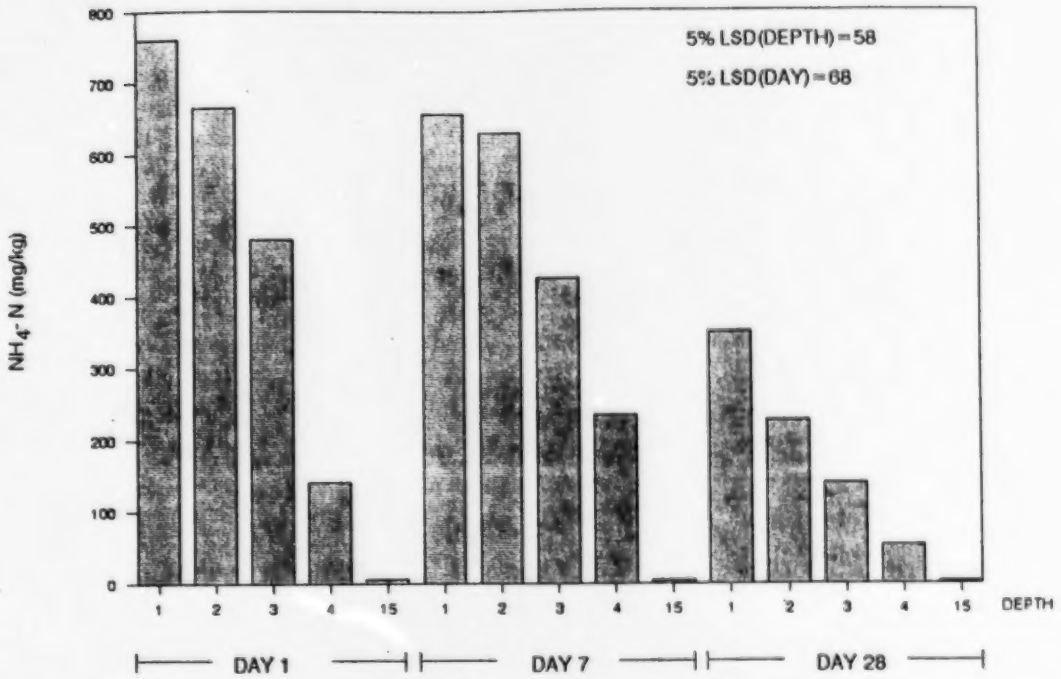

Figure 16. Exchangeable NH_4-N in Honeywood loam in Exp. 2.

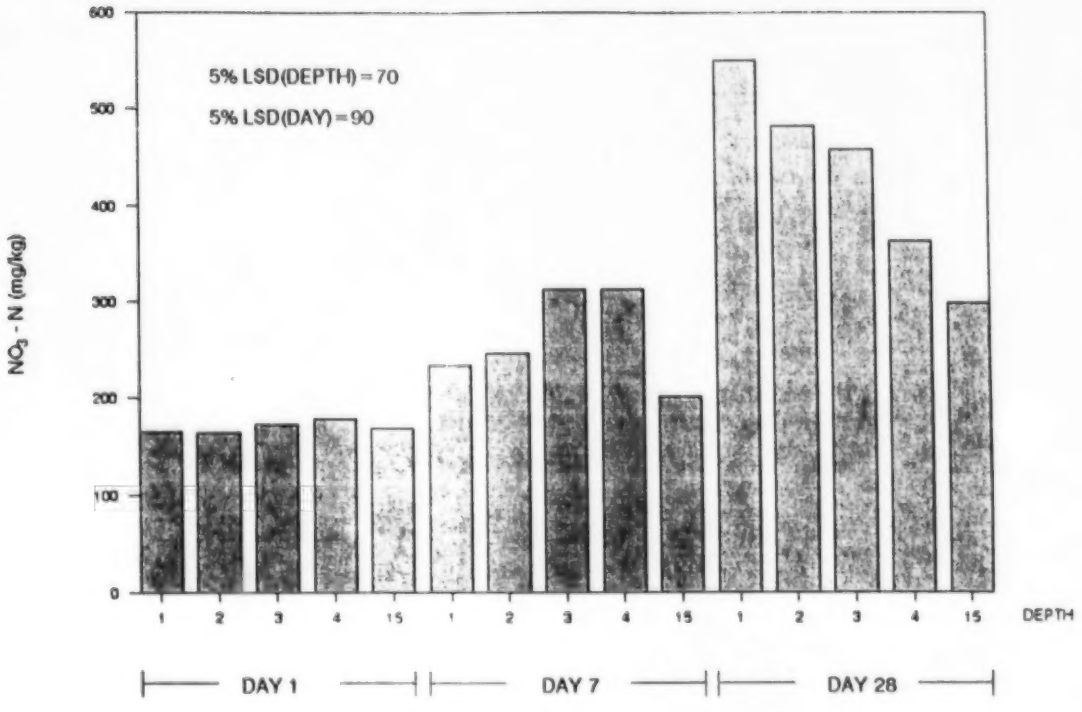

Figure 17. Nitrate-N in Honeywood loam in Exp. 2.

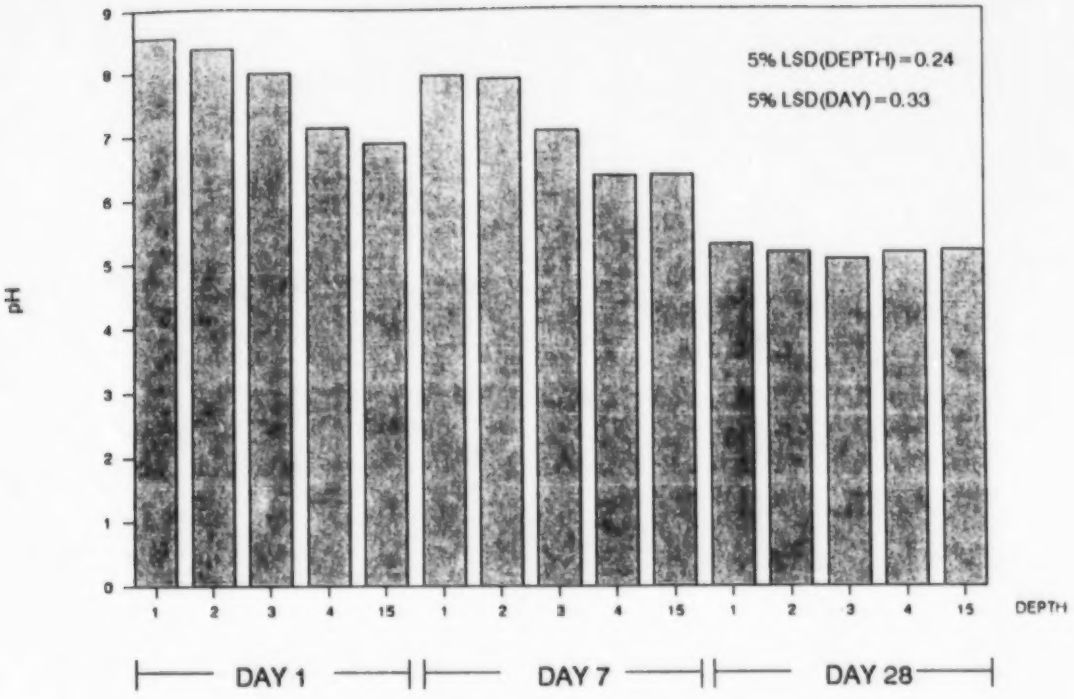

Figure 18. Soil pH for Honeywood loam in Exp. 2.

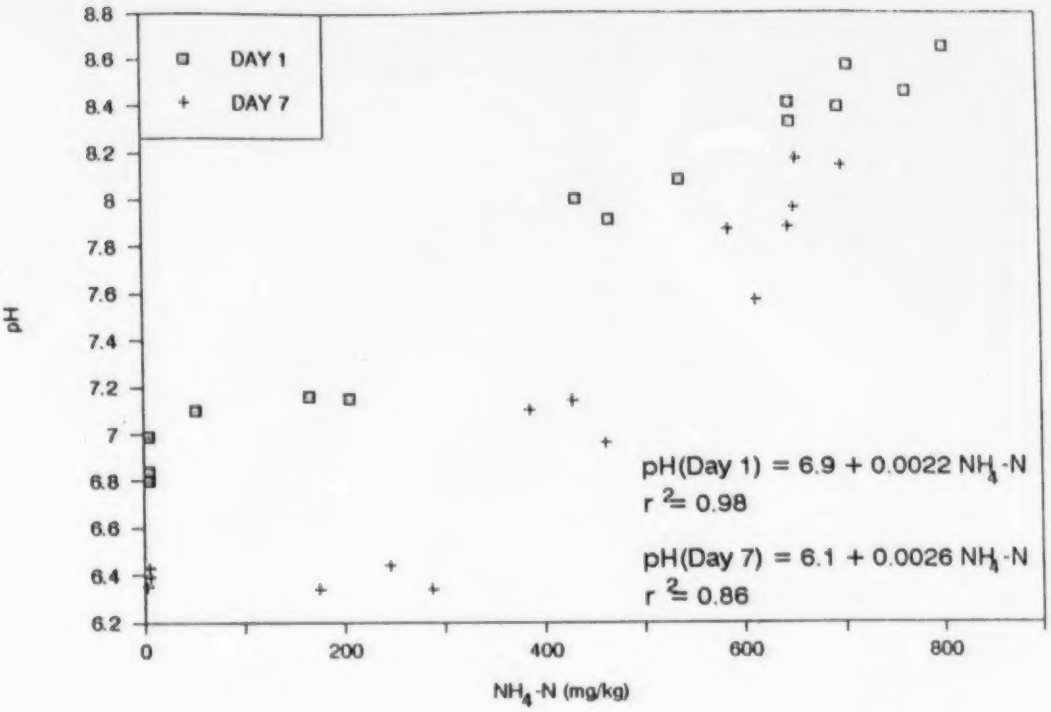

Figure 19. Plot and regressions of pH versus NH_4 -N for Honeywood loam in Exp. 2.

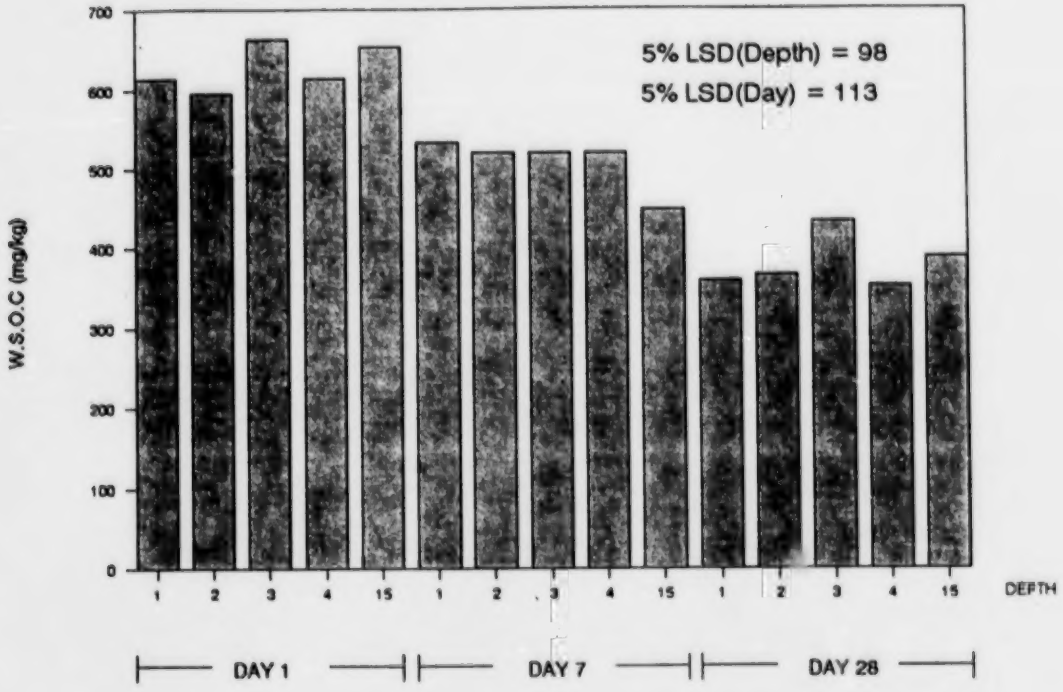

Figure 20. Water soluble organic C in Honeywood loam in Exp. 2.

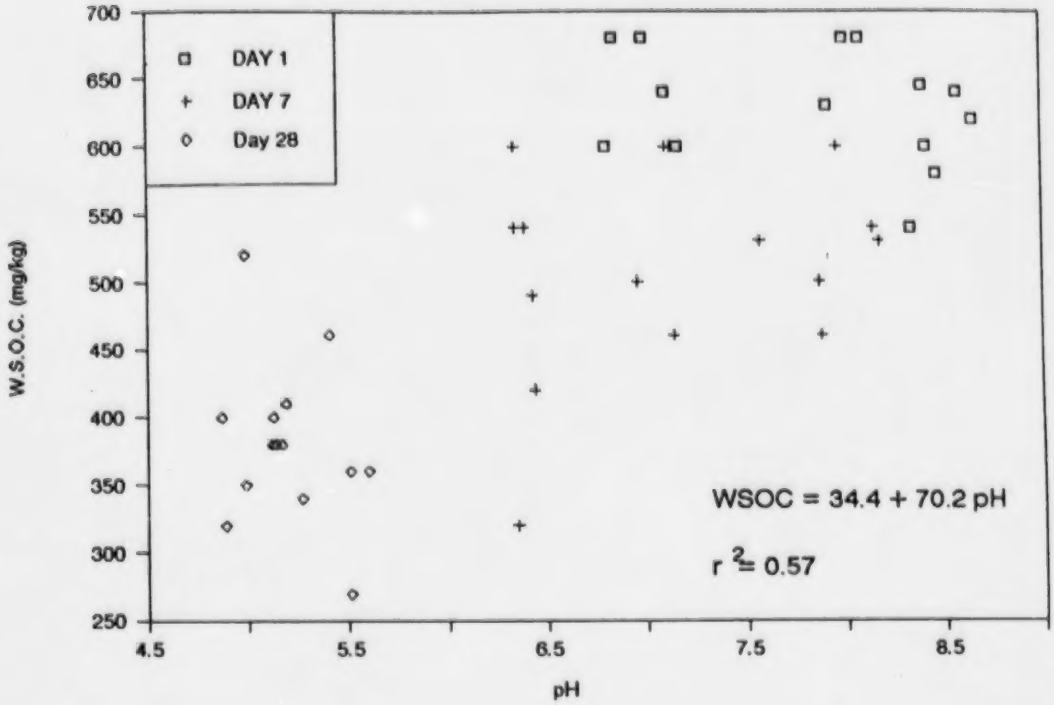

Figure 21. Plot and regression of water soluble organic C versus pH for Honeywood loam in Exp. 2.

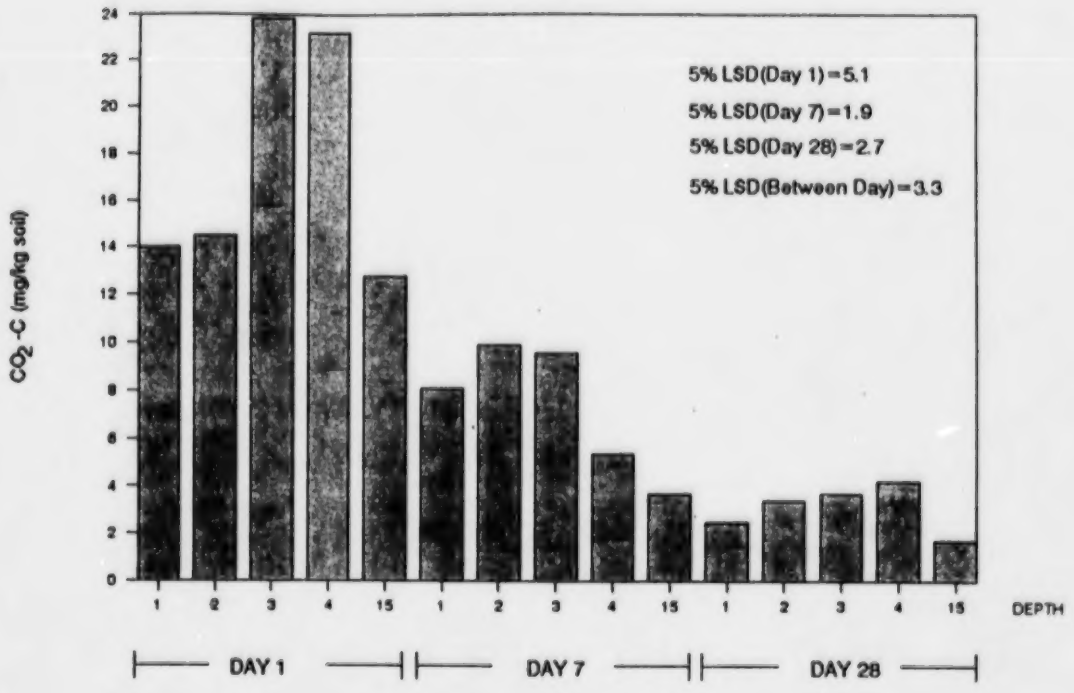

Figure 22. Production of CO_2-C by Honeywood loam in Exp. 2.

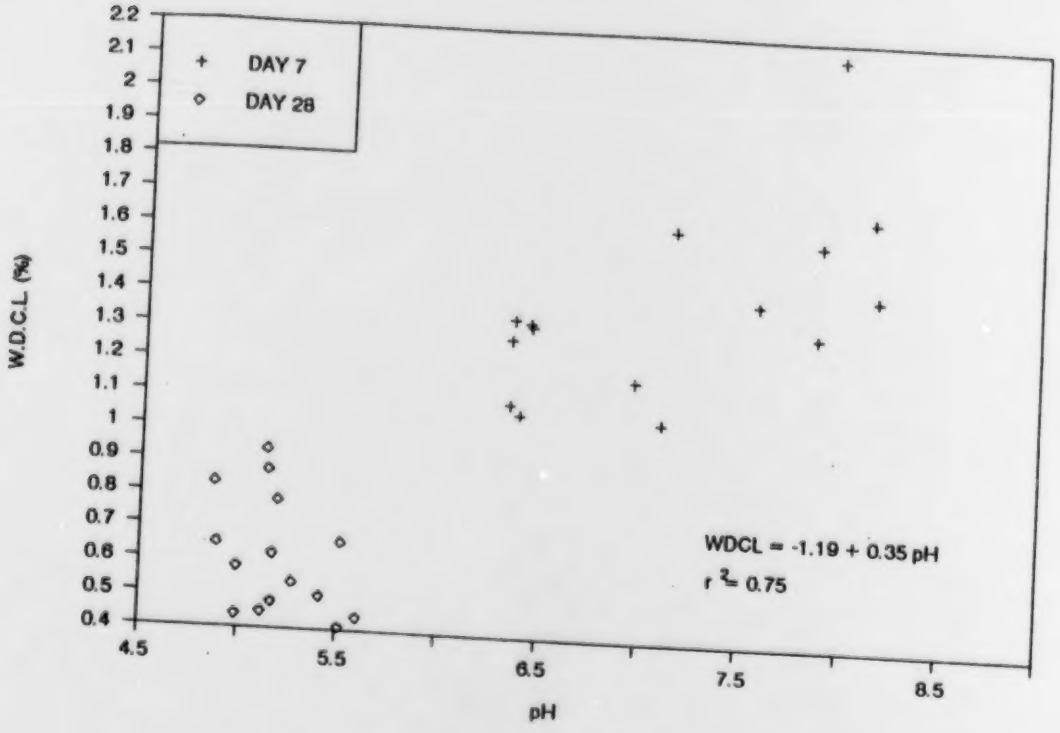

Figure 23. Plot and regression of water-dispersible clay versus pH for Honeywood loam in Exp. 2.